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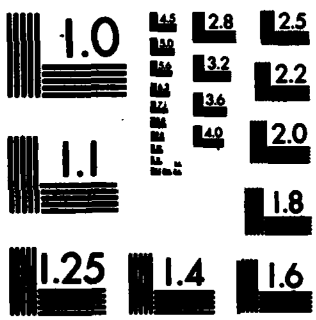
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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

COMPUTERIZED MEASUREMENT AND

TRACKING OF ACOUSTICAL RESONANCES

by

Donald Vincent Conte

December 1982

Thesis Advisor: S. L. Garrett

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A system is described which incorporated a Hewlett-Packard 85 "desk-top" computer to control a frequency synthesizer and read the output of a lock-in analyzer to measure, display and record the resonant frequencies, amplitudes, and quality factors of several modes of an acoustical resonator. The system is capable of locating, measuring, and tracking the resonant modes as parameters which affect sound speed and attenuation are varied. An algorithm for rapidly fitting "good quality" measured data to a resonance

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Computerized Measurement and Tracking of Acoustical Resonances

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the requirements for the degrees of

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ABSTRACT

A system is described which incorporated a Hewlett-Packard 85 "desk-top" computer to control a frequency synthesizer and read the output of a lock-in analyzer to measure, display and record the resonant frequencies, amplitudes, and quality factors of several modes of an acoustical resonator. The system is capable of locating, measuring, and tracking the resonant modes as parameters which affect sound speed and attenuation are varied. An algorithm for rapidly fitting "good quality" measured data to a resonance lineshape is described which determines quality factors to precisions of better than 0.1 percent, amplitudes to better than 0.01 percent and center frequencies to better than 0.1ppm. Sample output is provided for the lowest three plane wave modes of an air filled cylindrical resonator in the temperature range of -15 to 25 degrees Celsius.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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I. INTRODUCTION

A. BACKGROUND

Many applications in physics and engineering require the ability to determine the center frequency (fo), maximum amplitude (A), and quality factor (Q) of a resonance. A few examples of this need arise in the measurement of the speed of sound, in the reciprocity calibration of electroacoustic transducers [Ref. 1], and in the measurement of sound absorption.

Prior to the advent of computers and instrumentation interfacing, severe limitations were imposed upon the experimental precision obtainable. The variation of amplitude at resonance is second order in frequency so that a small uncertainty in the maximum amplitude results in a greater uncertainty in the frequency corresponding to the maximum amplitude. Also, the Q is calculated from the ratio of a large number (center frequency) to the difference of two large numbers which may differ by a small amount (the 3 dB down frequencies), resulting in an uncertainty in Q which can be quite large.

This project was designed to produce an automated, high precision system capable of obtaining and tracking the center frequency, maximum amplitude and Q of several acoustical resonant modes in any given resonator as some external parameter affecting these values is varied. The approach was broken up into four task groups.

1. <u>Acoustical Signal Generation and Detection</u>

It was necessary to determine which method of resonance excitation and signal detection was best suited for automated data acquisition and analysis. The following are the three techniques examined experimentally:

a. swept frequency continuous wave excitation with tracking narrowband heterodyne reception using an HP 3580A spectrum analyzer.
b. phase-sensitive detection utilizing a two-phase lock-in analyzer and a programmable frequency synthesizer as a signal source.
c. broadband noise excitation in conjunction with an FFT analyzer.

2. <u>Data Analysis Program Development</u>

It was necessary to determine a precise and efficient computer algorithm for the fitting of the resonance data to a resonance lineshape to extract fo, A, and Q.

3. System Implementation

This involved the assembly of the required components (computer, analog-to-digital converters, counter, etc.) in a custom rack, interfacing and interconnection of components to the computer, resonator, and each other, and the writing of the software to allow the computer/controller to orchestrate all of the acquisition, analysis and display functions.

4. System Test and Evaluation

The final task was to test the system on the lowest frequency plane wave modes of a gas filled, cylindrical resonator to determine: the precision with which amplitude, Q and center frequency could be measured; the tracking capabilities; the processing speed; and the utility of the output.

B. CONCLUSIONS FROM TASK COMPLETION

Upon completing tasks 1 and 2, it was determined that method b (frequency synthesizer/phase-sensitive detector) provided the best noise rejection and resolution, was computer controllable, and resulted in a data set which simplified the implementation of the resonance fit algorithm chosen from task 2. Method a of task 1 was rejected due to

the lack of a suitable computer interface which would allow automatic changes in frequency range. Also, the sweep would require catching the values "on the fly" thus resulting in inaccuracies which were sweep rate dependent and data points which were not necessarily equally spaced. Method c was not utilized due to the inability to concentrate the energy in the bands of interest, resulting in the need for higher power to the resonator without an increase in the signal to noise ratio in the frequency domain of interest.

The completion of all of these tasks resulted in the system to be described in the remainder of this thesis. The system is capable of a precision equal to or better than one part in 10^7 in frequency, one part in 10,000 in amplitude, and one part in 1000 for Q.

II. EQUIPMENT SETUP AND DESCRIPTION

A. EQUIPMENT SETUP AND INTERFACE

Figure 1 shows a block diagram of the equipment utilized in the final system. The following is a brief look at the overall function of the system which will be followed by a description of each individual piece of equipment.

The HP-85 computer directly controls all of the equipment, with the exception of the Lock-in Analyzer, via the Hewlett Packard Interface Bus (HPIB). The computer sends a value for frequency and amplitude to the HP3325A Synthesizer/Function Generator, which causes an excitation of the acoustic resonances in the resonator. The amplitude analog signal received by the lock-in analyzer is converted to a D.C. voltage which is sent to the HP3497A Data Acquisition/Control Unit where it is digitized prior to being sent to the computer via the HPIB. After processing, the computer sends output to the HP2673A Printer and the HP7470A Graphics Plotter. The HP3456A reads the temperature in degrees Celsius from a thermistor mounted in the body of the resonator and, when interrogated by the HP-85, sends the current value via the HPIB. In the test system (Chapter IV) the HP3325A outputs the required frequency and amplitude

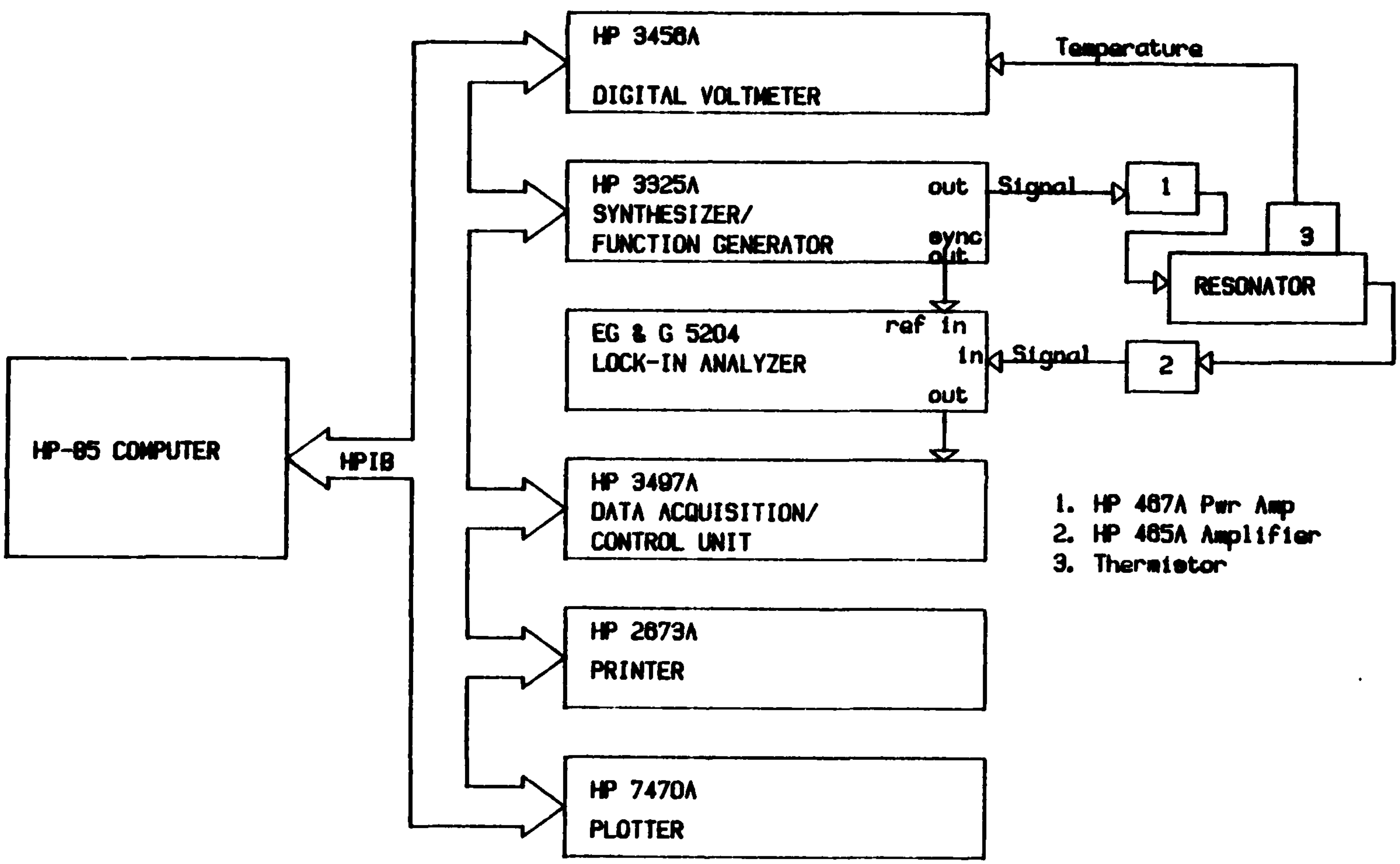


FIGURE 1 BLOCK DIAGRAM OF SYSTEM

signal by means of a power amplifier to the electret transducer at one end of the resonator. An electret transducer at the other end of the resonator picks up the signal and sends it via an amplifier to the EG&G 5204. The EG&G 5204 is phase-locked to the HP3325A and outputs a D.C. voltage which is proportional to the Pythagorian sum of the amplified in-phase and quadrature components of the signal. This analog amplitude is sent to the HP3497A which, when interrogated, sends via the HPIB, a digital measurement of the voltage level. The HP-85 also outputs values to the HP2673A and HP7470A to be printed and plotted respectively.

B. EQUIPMENT DESCRIPTION

1. HP-85 Computer

The Hewlett-Packard Personal Computer (HP-85) is an 8 bit microcomputer containing as standard a 16K byte memory, a built-in thermal printer and a small CRT. The computer is programmed in BASIC computer language. As utilized in this application, the memory was expanded to 32K bytes through the use of an add-on 16K byte memory module (#52903A). In addition, the HPIB interface (#82937A), and the ROM Drawer (#82936A) with a plotter/printer ROM (#00085-15002) and input/output ROM (#00085-15003) were utilized.

The HPIB is Hewlett-Packard's implementation of the IEEE Standard 488-1975 and is a parallel bus of 16 active signal lines, 3 data control lines and 5 interface management lines. It is capable of interconnecting up to 15 instruments. The input/output and printer/plotter ROMs further expanded the memory in order to handle the transformations necessary to transmit information via the HPIB to the peripherals.

2. Digital Voltmeter HP3455A

Although the HP3456A has numerous capabilities, in this application it was only utilized as a means to obtain a temperature from a thermistor and to transmit that value via the HPIB to the HP-85 computer. Its only utilization was to demonstrate the system's ability to track resonances under conditions of varying temperature.

3. Synthesizer/Function Generator HP3325A

The HP3325A has a frequency range from 1 microhertz to 20 megahertz with a resolution of up to eleven digits. The peak to peak output amplitude can be set from one millivolt to ten volts. It is fully programmable via the HPIB and was so utilized in this application. The execution time for a frequency command via the bus is 7.0 msec plus

2.8 msec for each digit plus 2.8 msec for a decimal plus 12.5 msec for each delimiter. The execution time for amplitude is 6.8 msec plus 2.8 msec for each digit plus 2.8 msec for a decimal plus 13.0 msec for a delimiter.

4. Data Acquisition/Control Unit HP3497A

The HP3497A was utilized as a voltmeter in this application. It received an analog voltage level from the lock-in analyzer which was proportional to the full scale meter deflection and converted it into HPIB compatible signals to be transmitted to the HP-85. It was completely program controlled, sampling and sending only when so directed by the HP-85.

5. EG&G Lock-in Analyzer Model 5204

Because the 5204 was not HPIB compatible, desired functions had to be manually controlled vice program controlled. This included changes to full-scale sensitivity and time constants. It received a phase reference synchronization signal from the HP3325A and the data signal from the resonator. Through vector manipulation it outputs the square root of the sum of the squares of the inphase and quadrature components of the amplified signal to the HP3497A.

6. Power Amplifier HP467A and Signal Amplifier HP465A

These were ordinary amplifiers inserted in the system to provide signal gain. The HP467A was set for a voltage gain of two to drive the resonator while the HP465A provided a gain of +20 dB for the output from the resonator.

7. Intelligent Graphics Printer HP2673A

The HP2673A prints bi-directionally at the rate of 120 characters per second with a 7 X 11 dot matrix character font in a 9 X 15 character cell with twelve character sets to choose from and three modes of formatting. This printer was utilized to obtain standard sized paper output vice the small sized thermal printer output of the HP-85. It was utilized in the fully program controlled mode.

8. Graphics Plotter HP7470A

The HP7470A was utilized to produce the high resolution and excellent quality graphs included in this report and suitable for publication. It is a two pen plotter capable of utilizing up to ten colors through programmed stops. It has a character plotting speed of up to six characters per second in any of five character sets with text written in any direction, with or without character slant, and in varying sizes. It was utilized in

the fully programmed mode via the HPIB. One of its nicest features is the ability to define the plotting area, thus giving the operator the capability of enlarging or shrinking the output size as desired. All figures in this thesis were produced on this piece of equipment. It is to be noted that although these figures are actual system outputs or replicas of system outputs, they were collected over a period of time which involved several experiments. Thus, each individual variable may not exactly coincide in value from figure to figure since parameters such as temperature, drive amplitude, full scale sensitivity, time constants, frequency band, etc., all affect each variable and were possibly different for the figures shown.

9. Thermistor

The thermistor utilized in this set up is an HP-0837-0164 resistive type with a range of -80 degrees Celsius to 150 degrees Celsius with an accuracy of plus or minus 6 degrees Celsius for the range of -75 degrees Celsius to 130 degrees Celsius. Because the temperature was only being utilized as an indicator of change, it was not necessary to measure this quantity accurately for this experiment. Thus, the most convenient means of

accomplishing the desired task was utilized. The thermistor has a nominal resistance of 5000 ohms at 25 degrees Celsius rising to 3.684 Mohms at -80 degrees Celsius and falling to 92.7 ohms at 150 degrees Celsius.

10. <u>Resonator</u>

A detailed schematic representation of the resonator utilized to test the system is shown in Figure 2 [Ref. 2]. Although this system can be utilized with any resonator, a description of the one actually used will be given.

The resonator is a cylindrical brass cavity with diameter and length equal to 2.54 cm. The ends are capped by simple electret transducers. A small slot (0.16cm X 1.6cm) at the cylinder midplane exists to allow gas to enter and leave the resonator (a helium recovery line) as utilized in another application [Ref. 2].

A permanently polarized 12 micron thick disk of teflon (the electret), aluminized on one side, is electrostatically held against a sand blasted metal electrode, which forms the electrically active element in the resonator, while the aluminized side is connected to ground.

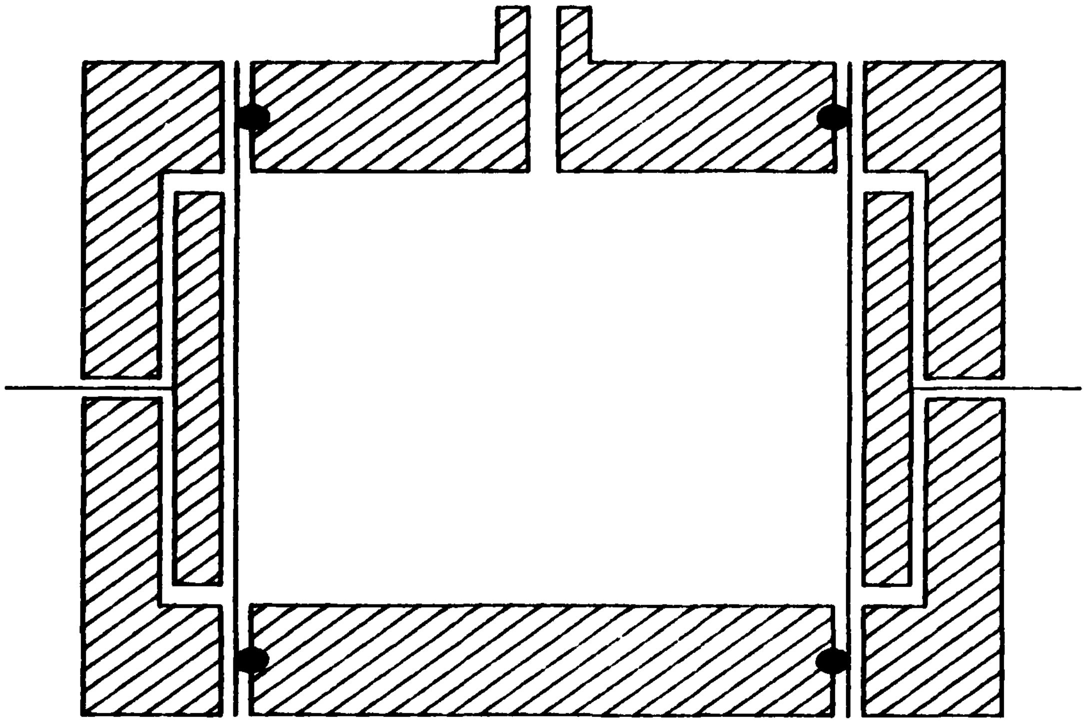


FIGURE 2 CROSS SECTIONAL VIEW OF RESONATOR

The use of pre-charged electret material eliminates the need for bias supplies ordinarily present in conventional capacitive transducers. The colored-in circles in the figure are o-rings utilized in assembling the resonator to provide a gas tight seal.

III. PROGRAM EXPLANATION

A simplified flow chart of the program is shown in Figure 3. A brief overview of the flow will be given followed by a description of the individual blocks.

The operator inputs an upper and lower frequency, a drive amplitude and a time constant. This time constant will be discussed later, but it also needs to be set on the lock-in analyzer as well as entered into the computer. This then constitutes the input to 'Search'. In 'Search', an approximate center frequency and amplitude is displayed for all resonances within the frequency band entered. The desired modes are chosen by the operator and carried into 'Sort'. In 'Sort' each of the modes is remeasured and then refined via a five point fit routine which results in an output of center frequency, maximum amplitude, quality factor, and bandwidth. A new time constant is determined and all are carried into 'Measure'. In 'Measure', a more accurate center frequency, maxium amplitude and Q are found for each mode. These then go into 'Ravine' where they are refined to a high precision by a modified Chi-squared minimization algorithm. The last step is 'Track' where each of the modes is continually checked as well as the resonator

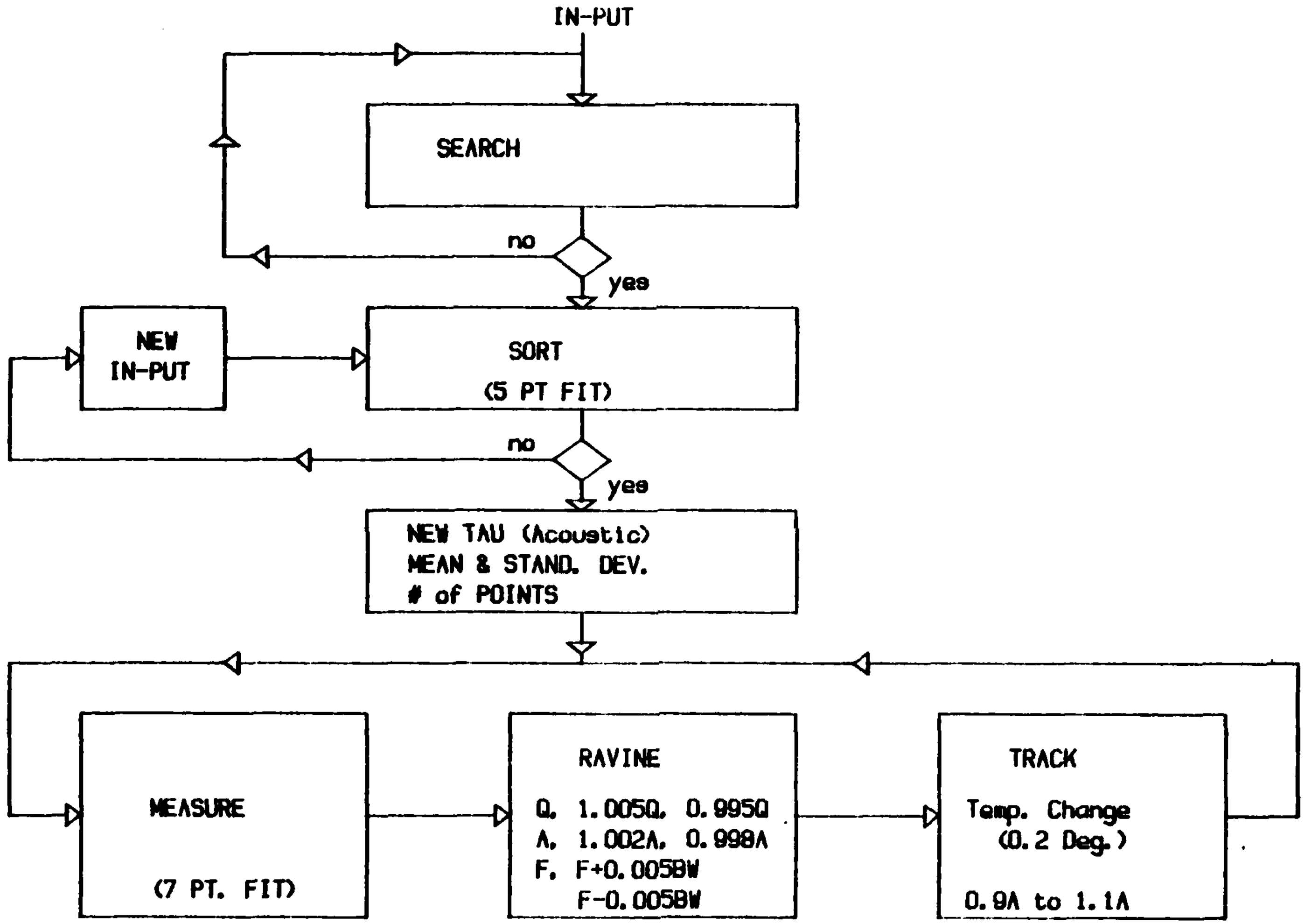


FIGURE 3 FLOW CHART OF PROGRAM

temperature until a change in any resonant amplitude of 10 percent or a difference in temperature of 0.2 degrees Celsius is detected at which time the program loops back into 'Measure' and repeats the routine.

It is appropriate, at this time, to state that throughout the program, any system equipment response times (as mentioned in Chapter II) necessary for data transfer/acquisition are allowed to elapse through the use of WAIT statements prior to sampling any given response.

A. INPUT

The operator selects a start frequency and an end frequency to define the frequency spectrum to be investigated. Also, a drive amplitude and maximum drive amplitude are selected, which can be any value up to and including 3500 millivolts (limit of the HP3325A Synthesizer/Function Generator). Two amplitudes are selected because later in the program the drive amplitude will automatically increment or decrement the value in order to keep the lock-in output in its midrange. The second value (max. drive) is a default value adopted should the program attempt to exceed it while incrementing the drive amplitude. Finally, a time constant (tau) is selected. The

lock-in analyzer divides the spectrum into 256 regions and integrates over each. The program calculates a maximum tau by

$$\tau = 256/4*(f_{upper} - f_{lower})$$

in order that there is not a space between regions and that the sensitivity over the region be nearly flat. This value is a maximum such that the operator selects a value available on the lock-in analyzer which is equal to or less than this and enters the value set on the lock-in, into the computer.

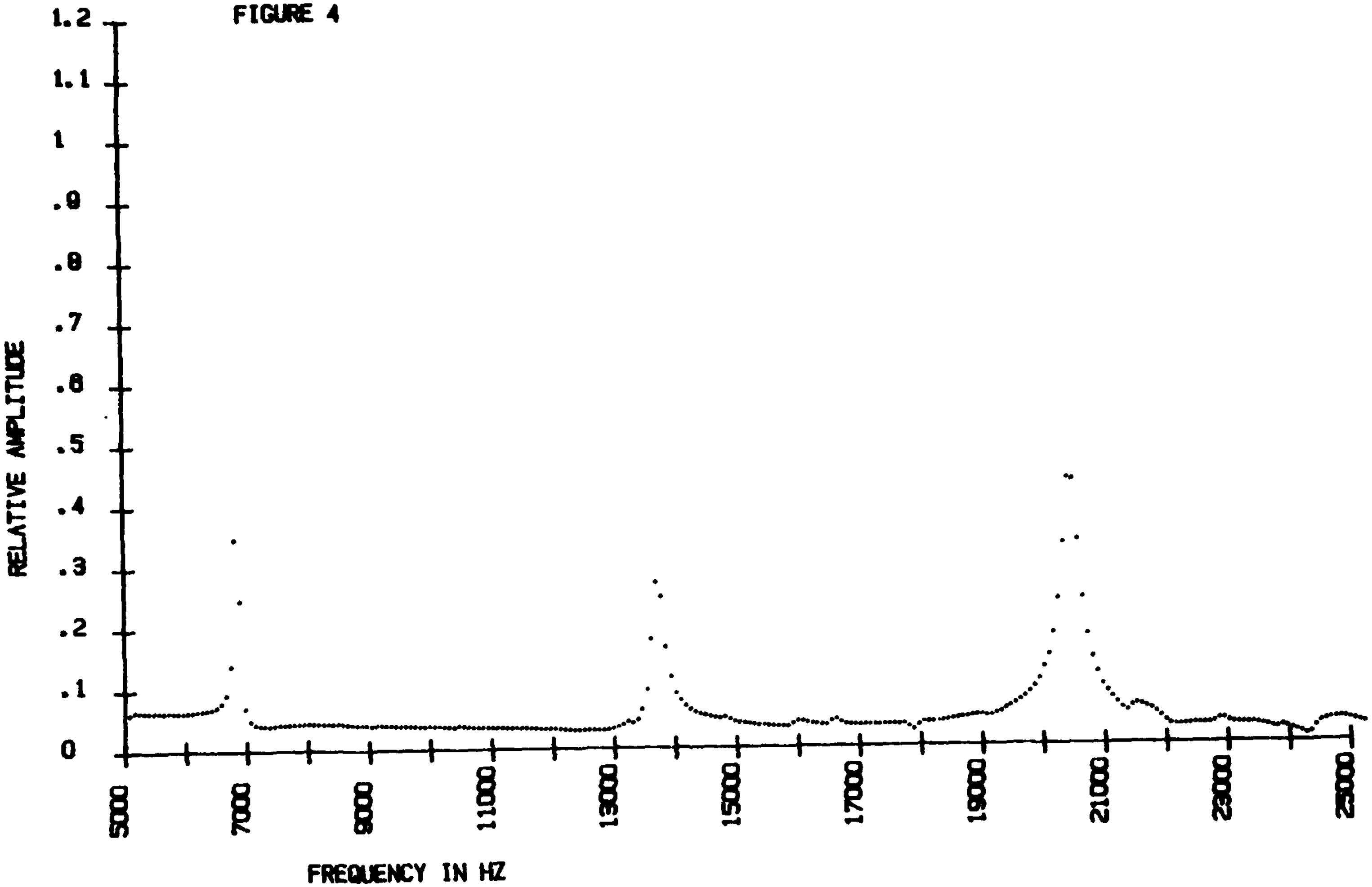
B. SEARCH

The frequency range is divided into 256 parts as mentioned above. Each of these frequencies is sent via the HPIB from the HP-85 to the HP3325A and a resonator amplitude value for each of these frequencies is obtained by the HP-85 from the HP3497A via the HPIB. There is a programmed delay (WAIT) of 4 tau between the sending of a frequency and the sampling of its amplitude in order to allow the resonator to attain at least 98 percent of its steady state value as determined by the lock-in integration time. The choice of 256 regions was dictated by the horizontal resolution of the

HP-65's CRT display. These 255 values are then plotted on the CRT with the option of a hardcopy printout from the HP7470A as in Figure 4. This graphically displays where each of the resonance modes within the specified frequency interval is located.

From Figure 4, it can be seen that not only are the responses from three major plane wave modes displayed but also those of several other (azimuthal, radial, mixed) modes. It is possible to concentrate on any mode displayed. After the operator enters a threshold relative amplitude value, the computer provides a printout on its thermal printer listing all amplitudes and their associated frequencies which equal or exceed this threshold value (see Table 2 in Chapter IV for printout). If the operator is satisfied with the output, then the plot and the thermal printout are utilized to input to 'Sort' the approximate center frequency and bandwidth for each desired mode. If the operator is not satisfied, the program loops back to 'Input', new parameters are chosen, and the process repeats itself.

FIGURE 4



PLOT OF RELATIVE AMPLITUDE VS FREQUENCY (FULL SPECTRUM)

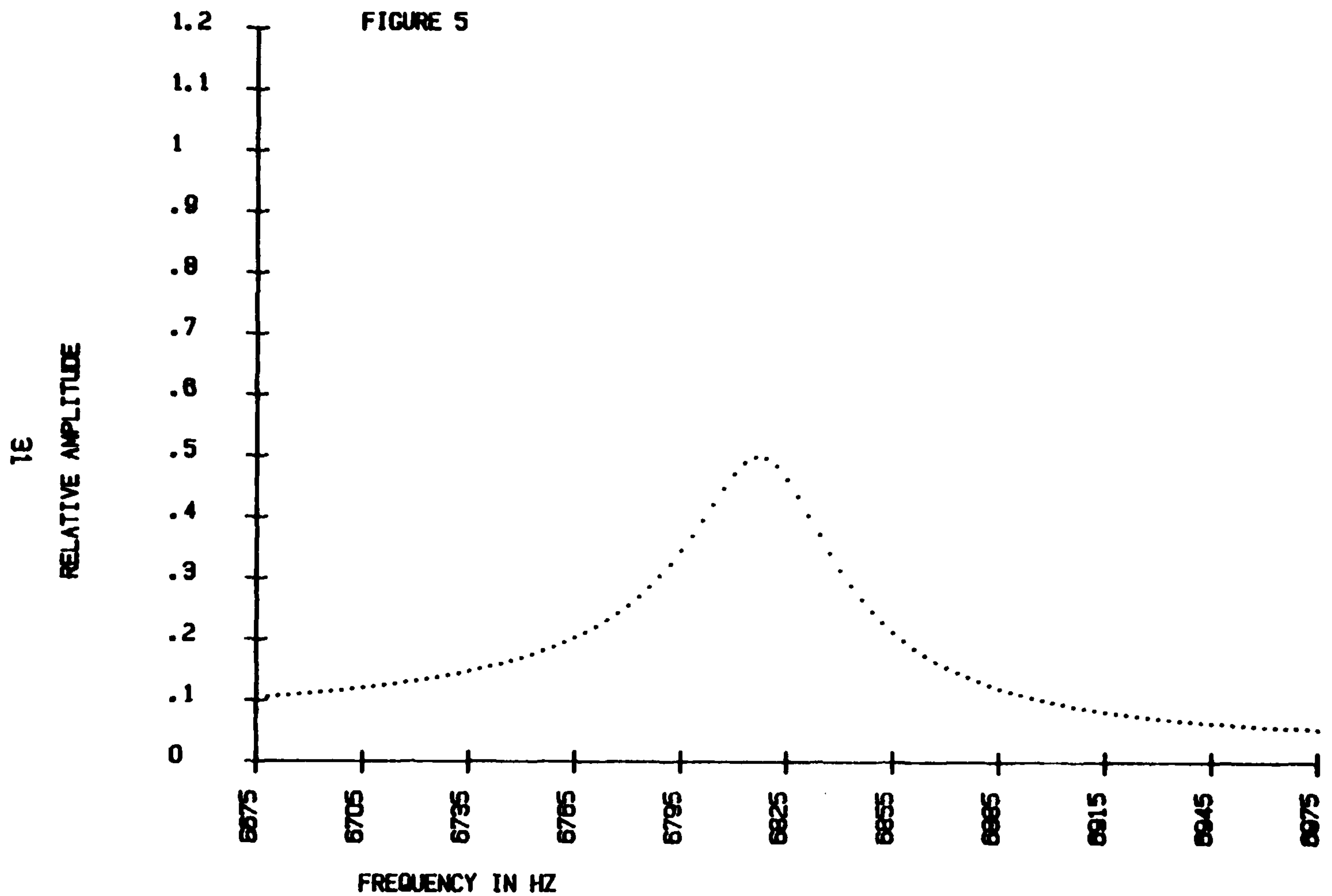
C. SORT

The purpose of 'Sort' is to identify for the computer the modes to be investigated and to obtain "reasonable" values of center frequency, maximum amplitude, and quality factor for each desired mode. "Reasonable", in this case, is defined as sufficiently accurate to allow these obtained values to be automatically controlled in 'Measure'. This is achieved by the operator inputting a center frequency and bandwidth for each mode desired to be worked upon. As configured, up to nine modes can be selected. However, this limit can be increased through a program/dimension change to whatever number is desired. Nine was chosen as a matter of convenience to simplify memory management.

In this portion, the bandwidth of each mode is divided into one hundred (an arbitrary number which gave sufficient resolution) equal frequency steps which are individually sent and their respective amplitudes collected in the same manner as in search.

Once again, a plot is generated on the CRT with the option for a hard copy (Figure 5). If the operator is not satisfied with the output, then the program loops back to the start of 'Sort' and new inputs are entered. If the

FIGURE 5



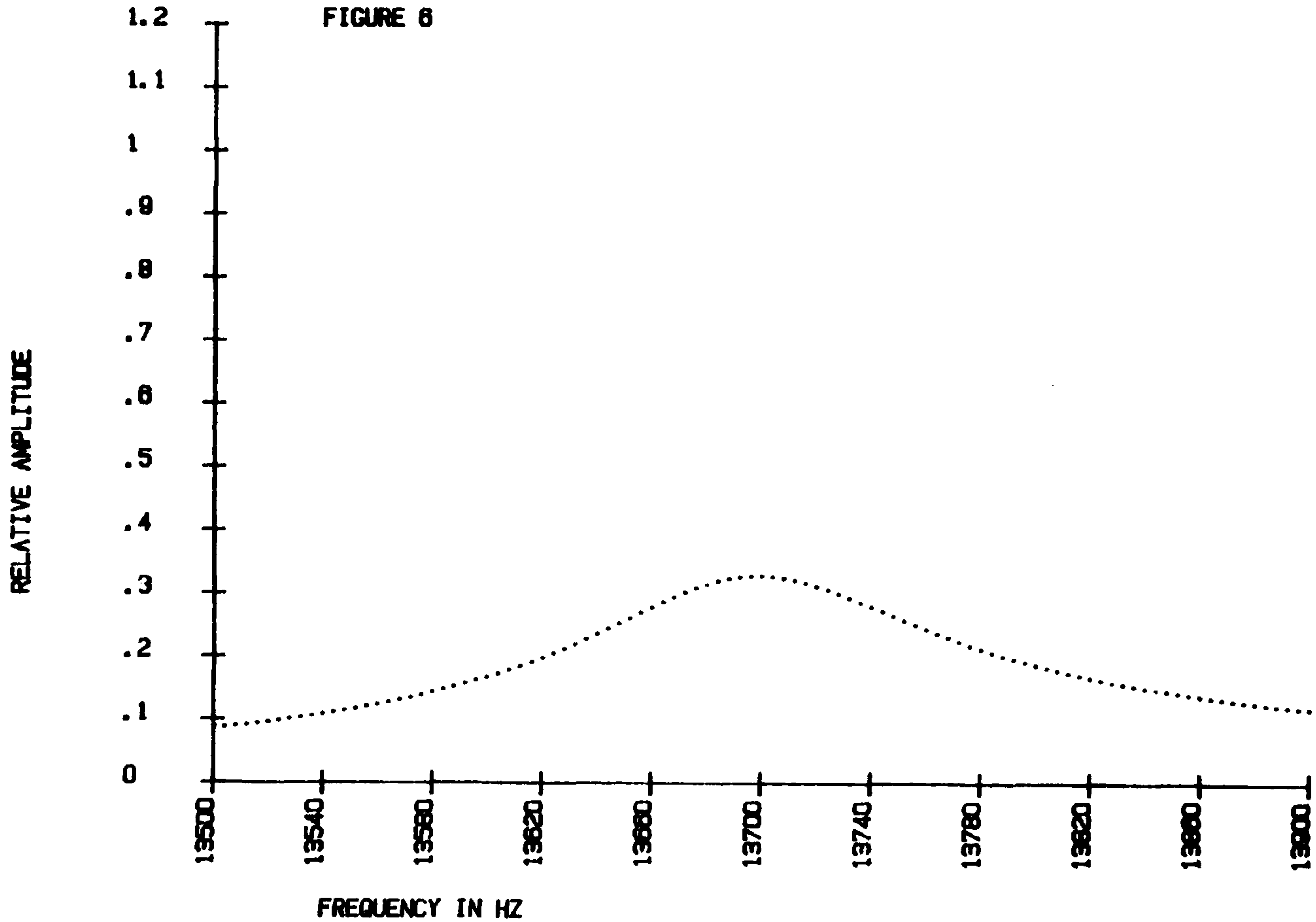
PLOT OF RELATIVE AMPLITUDE VS FREQUENCY. MODE 1

operator is satisfied, the program finds the maximum amplitude and its corresponding frequency (center frequency). This is accomplished by examining the value of the amplitude of each of the one hundred points and selecting the one which is greatest. The amplitude value of the 3 dB down points is then found from this maximum amplitude. The program again sorts through all of the points and finds the closest "bracketing" points to this calculated 3 dB down point. A linear interpolation is then utilized to calculate the corresponding frequency for the calculated 3 dB down amplitude point. Of course this process occurs twice since there is both an upper frequency and a lower frequency for the 3 dB down amplitude value. This process constitutes the "five point fit".

From these values, a quality factor is calculated which is equal to the center frequency divided by the difference of the upper and lower 3 dB down frequencies. This value, as well as the center frequency and maximum amplitude, is output to the HP-85 thermal printer (see Table 2 of Chapter IV for printout).

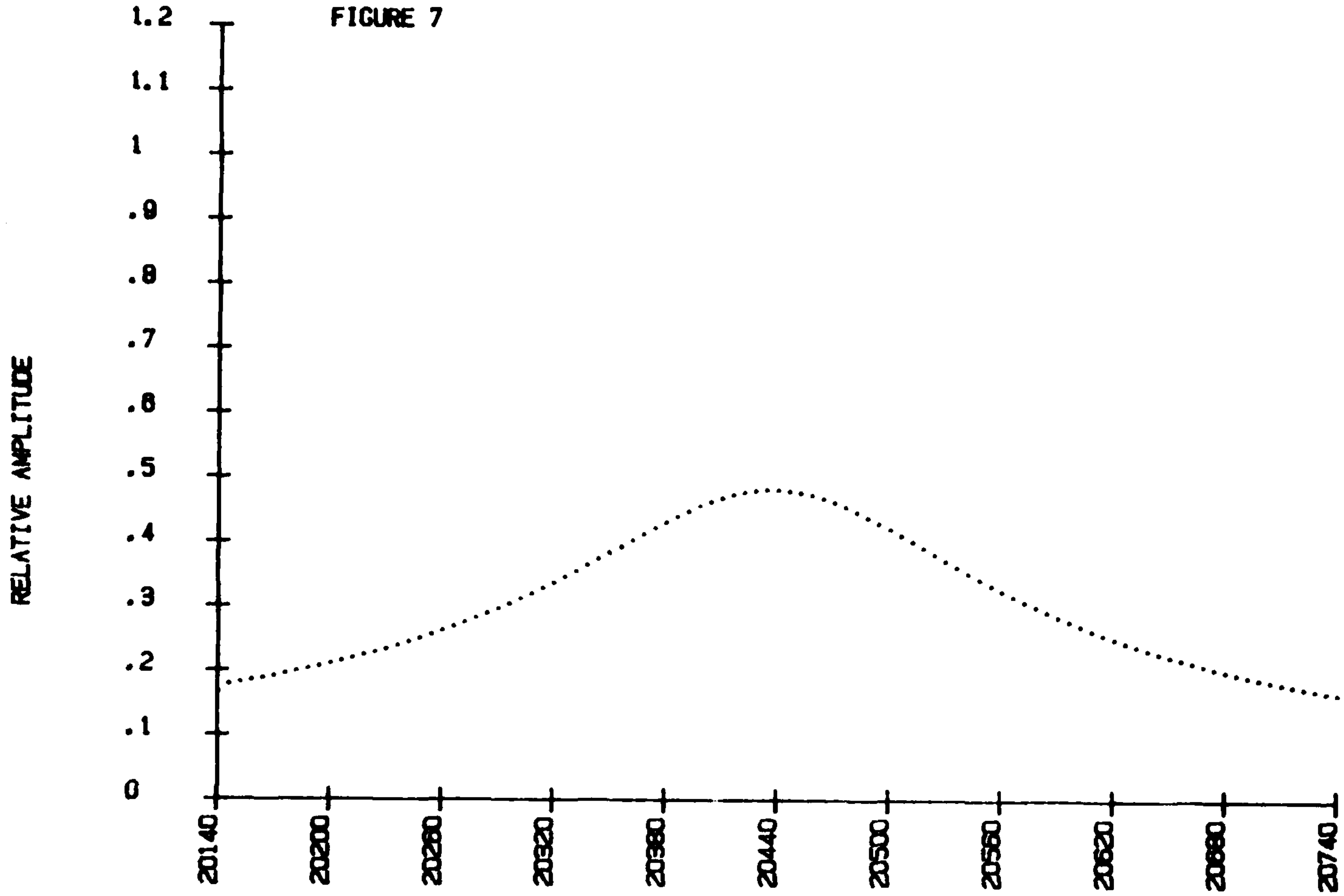
This procedure is repeated for each of the remaining modes. Figures 6 and 7 are the plotter outputs of the other

FIGURE 6



PLOT OF RELATIVE AMPLITUDE VS FREQUENCY. MODE 2

FIGURE 7



FREQUENCY IN HZ

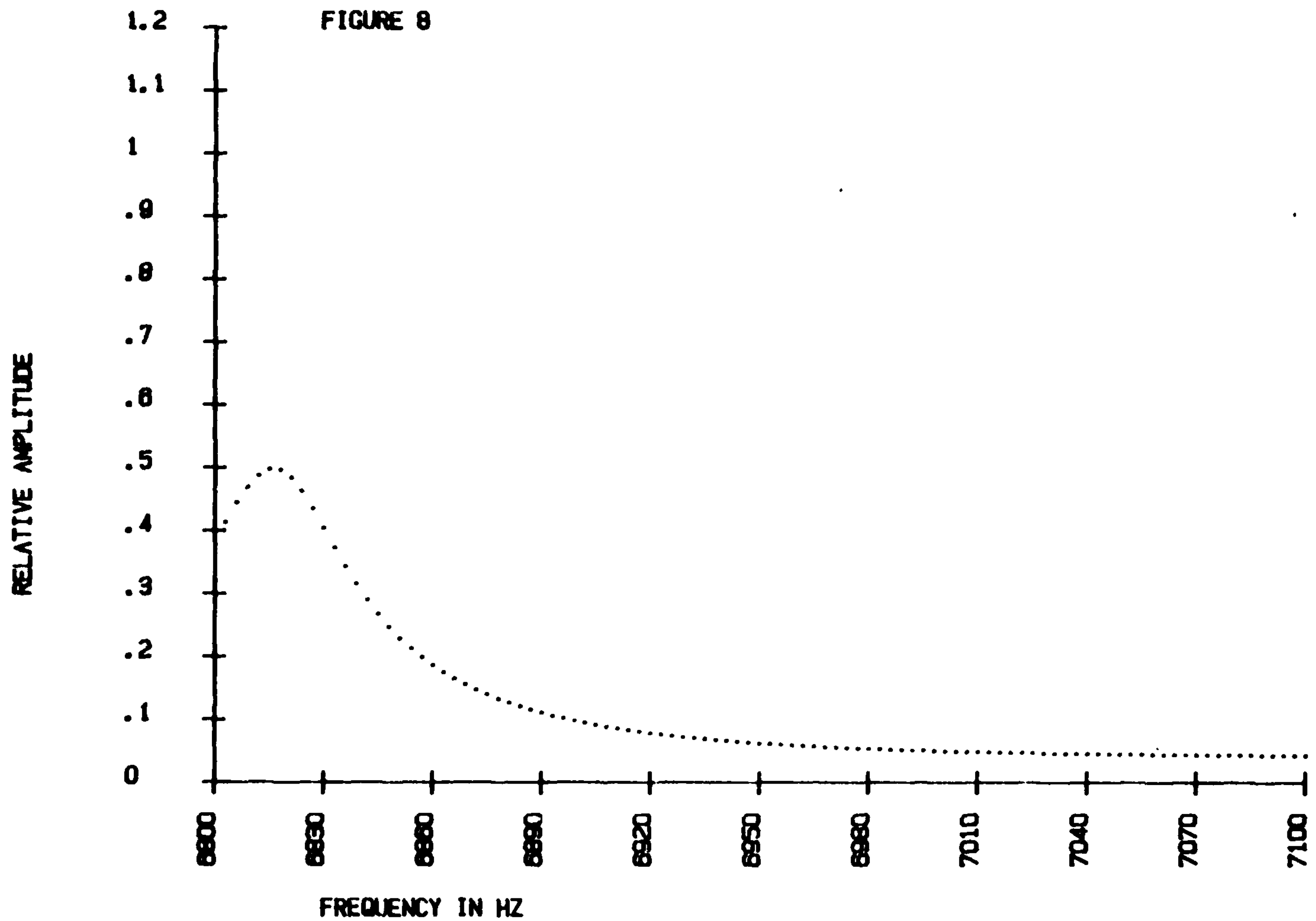
PLOT OF RELATIVE AMPLITUDE VS FREQUENCY. MODE 3

two normal modes investigated in this example. Figure 8 is an example of one possible reason for desiring to request a new input (wrong center frequency). In this case, it is possible that one of the 3 dB down points could not be found from the data (out of range). From this graph, the operator would obviously either choose a new center frequency input or increase the bandwidth such that the 3 dB down point would occur in the data.

D. NEW TAU

In this block, three things occur. First, a new time constant is found. This time constant is the acoustic time constant required for each point to attain 63 percent of its steady state value. This is in analogy with the time constant required for a capacitor in an electrical circuit to charge up to its full value. The acoustic time constant for each mode is found by dividing the Q for the mode by PI times the center frequency of the mode. Because of the manner in which Q is found, this equates to dividing one by PI times the difference of the 3 dB down upper and lower frequencies. After calculating the time constant required for each mode, the new system time constant selected is the greatest one required, thus insuring that the worst case is adequately covered.

FIGURE 8



PLOT OF RELATIVE AMPLITUDE VS FREQUENCY. MODE 1

Second, the background noise level is determined by the following method. The synthesizer outputs a frequency off resonance into the resonator and the lock-in analyzer is sampled one hundred times. The mean and the standard deviation of this set of measurements is calculated. The standard deviation is equated to the noise of the system. It is utilized later in determining the signal to noise (SNR) ratio for each mode. It is also utilized in the calculation of the third item of this block which will be described next.

The final (third) item is the examination of each mode to determine the maximum number of points which can be taken without having the possibility of the amplitude value of two adjacent points being equal or in the worst case inverting position due to associated uncertainties or random system noise. If the frequency step size (Δf) is large enough, then

$$\Delta A = A_{max} - A(fo+\Delta f)$$

can be chosen so that the inversion will not occur. Assuming a Rayleigh distribution lineshape then

$$A(f) = \frac{A/Q}{\left[\left(\frac{f}{f_o} - \frac{f_o}{f}\right)^2 + \frac{1}{Q^2}\right]^{1/2}}$$

Replacing f with ($f_o + \Delta f$) and $\epsilon = \Delta f/f_o$, the resulting equation is

$$\Delta A = A\left[1 - \frac{1}{[(2\epsilon Q)^2 + 1]^{1/2}}\right]$$

For the system described, 24 points are normally taken in a frequency range of 2 BW where $Q = f_o/BW$. Therefore, the following equation results:

$$2\epsilon Q = 2\,\Delta f/BW = 1/6 < 1$$

and, that quantity squared is <<1. Expanding and dividing by A

$$\frac{\Delta A}{A} \approx 2\,(\epsilon Q)^2 = 2\left(\frac{\Delta f}{BW}\right)^2$$

If A is chosen to be some number of standard deviations, σ, based upon the noise measurement, then

$$\frac{N\sigma}{A} = \frac{N}{SNR} = 2\left(\frac{\Delta f}{f_o} Q\right)^2$$

where σ/A is 1/SNR (signal-to-noise ratio). Now, Δf is found to be

$$\Delta f \geq \sqrt{\frac{N}{2(SNR)}} \quad \frac{f_o}{Q}$$

If I is the number of points to be taken in 2 BW then

$$I \leq \frac{2\,BW}{\Delta f} = \frac{2 f_o}{Q \Delta f} = \sqrt{\frac{8(SNR)}{N}}$$

If the probability of an inversion, as described above, is set at 0.1 percent, then N = 3.3 based upon a standard distribution curve. It is worth noting at this point, that the probability of inversion away from maximum is everywhere

lower until the signal level is on the order of the background noise. Utilizing the 0.1 percent criteria, I < = 1.56*SQR(SNR). This number (I) is output to the HP-85 thermal printer. The program then defaults to twenty-four points as a minimum. This value was based upon a calculation from the Nyquist sampling rate. The minimum from the Nyquist sampling rate (in integer value) would be three; but it is generally agreed upon in engineering applications that a factor of three or four is required in order to obtain a satisfactory reproduction of the signal. At this point the bandwidth was doubled to insure inclusion of the 3 dB down points and thus the minimum number of points obtained equalled 24. For this choice the requirement that an inversion due to noise has a probability of 0.1 percent or less requires the SNR to equal or exceed 237 (+47.5 dB).

The system has worked when the indicated number of points was as low as 10 (still defaulting to a choice of 24) but occasionally gave faulty values due to the reasons discussed above. Although it did not always happen, it is recommended that whenever the indicated number of points falls below 24, either the SNR is improved (increase drive

amplitude, etc.) or the mode is not suitable for further investigation. A sample of the thermal output format for tau, noise and number of points, is shown in Table 2, Chapter IV.

E. MEASURE

Each resonance mode has a frequency band calculated for it in 'Measure'. This band is twice the band defined by the 3 dB down bandwidth. Also, the relative value of the amplitude for the center frequency is evaluated to ascertain the need for adjustment in the drive amplitude. This is achieved by driving the resonator at the center frequency of each mode and sampling the amplitude value. If it is between 0.3 and 0.95 as measured on the Data Acquisiton System, then no adjustment is necessary. If it is not within these limits, it is either doubled or halved depending upon whether it was above or below the limits. This new value is again tested in the above manner until it is either within the limits or has exceeded the maximum drive amplitude which was set back in 'Input'. If this happens (exceeding), then the system defaults to the set value of maximum drive amplitude. This adjustment is necessary because the full scale sensitivity setting on the

lock-in analyzer is a manual rather than computer controlled function.

In 'Measure' the resonator amplitudes are obtained in the same manner (frequency sent--amplitude measured) as in 'Sort', only this time, twenty-four frequencies vice one hundred are utilized and the 'WAIT' becomes 12 tau which allows the system to reach within 6 ppm of the steady state value to fully utilize the 5 1/2 digit A-to-D conversion of the HP 4397A (as explained previously at the end of 'NEW TAU'). Once the data are collected, the following seven point fit is applied. The maximum amplitude point and the closest adjacent points on either side of it are used to define a parabolic curve. The maximum amplitude of this parabola and the corresponding center frequency are found by setting the first derivative of the amplitude with respect to frequency to zero. Solution of the resulting equations and subsequent insertion of the solution into the original equation yields a unique maximum amplitude and center frequency. This amplitude is then utilized in the calculation of the 3 dB down amplitudes. Frequencies corresponding to the 3dB down points are then found by linear interpolation in the same manner as previously

described in 'Sort'. A new quality factor is calculated utilizing these new frequencies and all three of these values; Q, maximum amplitude and center frequency are sent into 'Ravine'.

F. RAVINE

The values for maximum amplitude, center frequency and quality factor determined by the seven point fit described in the previous section ('Measure') are substantially more precise than those possible using conventional techniques employing a wave analyzer or spectrum analyzer under manual control. However, the high speed numerical processing ability of the digital computer allows a greatly expanded treatment of the data for only a minimal investment in actual processing time.

Implicit in the assignment of A (amplitude), fo (frequency), and Q (quality factor) as the three parameters which characterize a resonance line shape (as is done throughout this thesis) is the assumption that the amplitude, as a function of frequency, near resonance can be described by:

$$A(fn) = A/Q\,[(fn/fo - fo/fn)^2 + (1/Q)^2]^{1/2}$$

where : A(fn) is the resonance lineshape
A is the calculated maximum amplitude
Q is the calculated quality factor
fo is the calculated center frequency
fn is the measured frequency (24 per mode)

Using all twenty-four points, it is possible to obtain the sum of the squares of deviations of the data from the resonance lineshape defined by a particular choice of A, fo and Q as:

$$S^2(A,fo,Q) = \sum_{n=1}^{24} [An - A(fn)]^2$$

where An is the measured amplitude of the n(th) data point and A(fn) is as above.

Conventional data analysis then accepts the "best choice" for A, Q, and fo as that which causes S^2 to be a minimum [Ref. 3]. This minimization for a linear function is a straight forward algebraic process. However, an analytic least square fit to a non-linear function requires matrix inversions. This, in turn, not only requires large blocks of memory and computer time, but also can easily lead to errors due to internal round-off or truncation of digits within the computer [Ref. 4]. For these reasons, the

following method was devised and utilized for each of the resonant modes being investigated. Briefly, S^2 was computed for small variations in A, fo and Q as well as for the originally computed values for these terms from the seven point fit. These S^2 terms were then utilized in a parabolic fit in an attempt to find those values of A, fo, and Q which would cause S^2 to be a minimum. Because the results of the seven point fit were already quite good, the procedure, briefly described above and expanded upon in the remainder of this section, converges very rapidly to an astonishingly high degree of precision. This precision will be analyzed and discussed in detail in Chapter V.

For the remainder of this paper, the sum of the squares of deviations (S^2) will be referred to as the C-G value, which was chosen for historical reasons.

One at a time, each of the three parameters (A, fo, Q) in the resonance lineshape (A(fn)) are varied. The following is an example to clarify this process.

First the C-G term for the calculated Q is found. Now Q is varied by +0.5 percent and a second C-G term is found. Finally, Q is varied by -0.5 percent and a third C-G term is found. These three C-G terms are used to define a parabolic

curve (Figure 9) and a new value for Q which minimizes the C-G term is found.

This new value of Q replaces that found in the seven point fit and becomes the new value to be inserted in the resonance lineshape. This time, however, A is the variable to be adjusted. Just as occurred with Q, C-G terms are found for A, A + 0.2%A, and A - 0.2%A. Again, these C-G terms are utilized in a parabolic curve minimization and a new value for A is obtained which now replaces the A found in the seven point fit. Finally these new values of Q and A are utilized to determine a new fo in the same manner. This completes one iteration of the process and thus provides these new values of Q, fo, and A for the next iteration. Each iteration refines the precision of the values of Q, fo, and A and provides this new set of values for the next iteration. This process is repeated until the next iteration contributes a negligibly small variation in the C-G value [Ref. 3].

In the actual program utilized, the terms were varied in exactly the order described because in the relative precision of the terms, Q was the least precisely known term (historically, this is always true). Since this was the

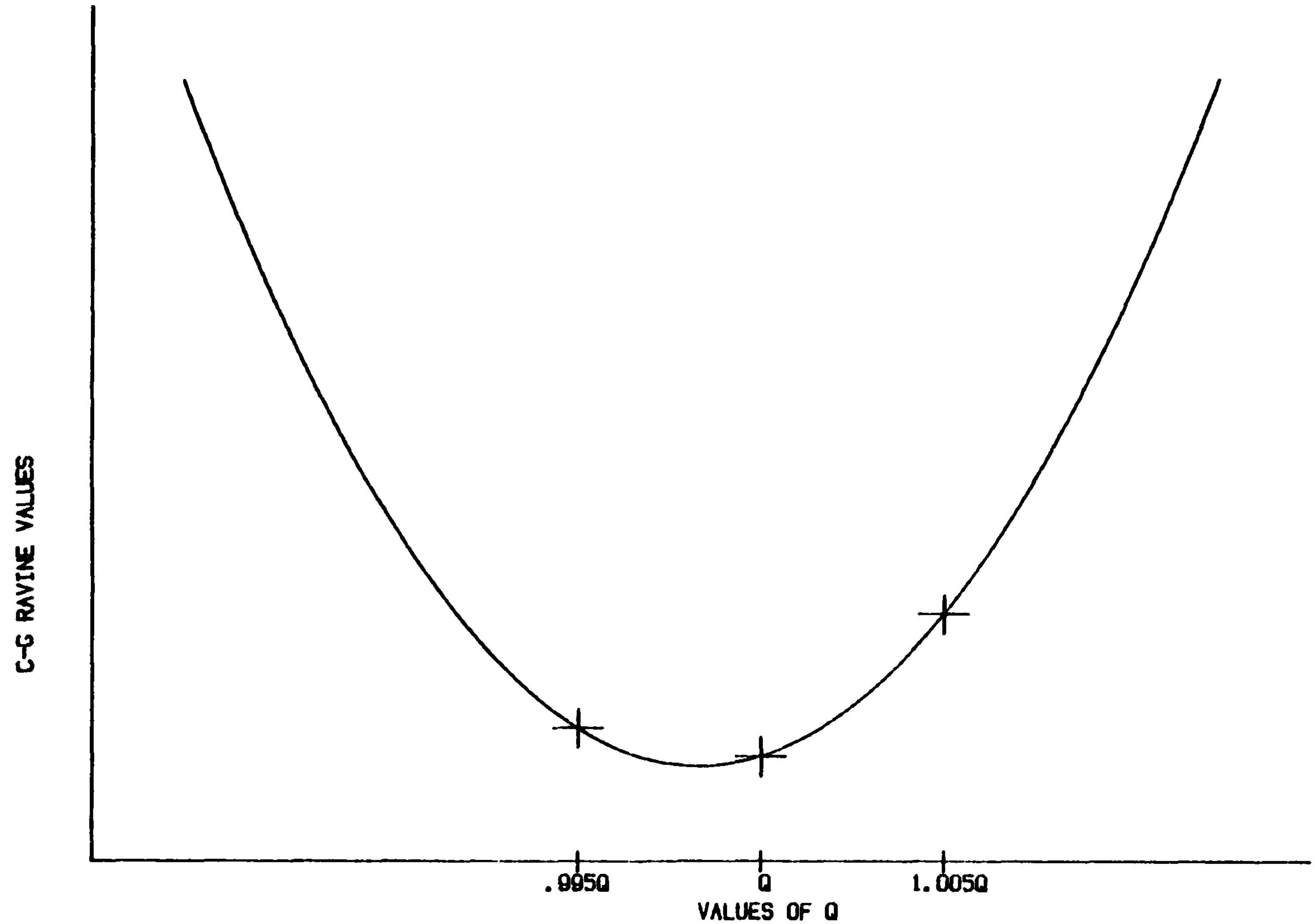


FIGURE 9 RAVINE PARABOLIC CURVE

case, varying it first resulted in the greatest effect. The next lowest precision term was A, so it was obviously the next choice to be varied. Finally, fo, which was actually well known, was varied. Because of the relative precision in Q, A, and fo the variations were arbitrarily chosen at the indicated values (0.5% of Q, 0.2% of A, and 0.005% of BW), as a matter of experience since these values reflected a sufficient variation for the 'RAVINE' technique to be effective. The better the approximations for Q, A, and fo put into 'RAVINE', the smaller these values can be made.

Upon completion of the final iteration (program dependent) the three newest values for Q, fo, and A are utilized to find a final C-G term which is then printed on the system printer and stored on a data tape. This C-G term is related to Chi-squared and may therefore be used to determine the "goodness of fit" [Ref. 3]. At this time, other parameters and variables are also printed on the system printer and stored on the data tape (time, temperature, pressure, mode number, fo, A, Q, SNR, drive amplitude, sequential data tape item number, and C-G Ravine value). These will be discussed at the end of Chapter IV and a sample output will be shown (Table 1).

If there are additional modes to be evaluated, then a loop is made back to 'Measure' and the next mode is evaluated in the same manner as described above. Upon completion of the final mode to be evaluated, the program shifts into 'Track'.

G. TRACK

In this portion the currently measured amplitude of each mode is compared with the measured value obtained during 'Measure'. If the value differs by +/- 10 percent (indicating a change in some external parameter), then the program loops back to 'Measure' to find the new Q, A, and fo for each mode. Also, the temperature of the resonator is measured and if a difference of 0.20 degrees Celsius is found then the system returns to 'Measure'. If neither the amplitude nor the temperature has met the criteria necessary to return the system to 'Measure', then the 'Track' section continually loops through itself until either of these criteria is met. The system remains in this endless loop of 'Measure', 'Ravine', and 'Track' until the operator causes the system to halt, the data overflows the available storage space on the data tape (850 mode entries) or a catastrophic system failure occurs (loss of power, etc.).

The preferable method of stoppage is to utilize a 'PAUSE' command from the computer keyboard since this enables continuation or program restart as desired. It is to be noted that any keyboard action will result in a halt. This, as well as any of the other mentioned halts (except 'PAUSE') may/will require re-loading the program into memory prior to re-running the system.

IV. SAMPLE EXPERIMENT

In order to test the system's ability to measure the stated quantities and to track the resonant modes as some external parameter was varied, an air filled resonator was cooled in a liquid nitrogen bath. This system was chosen for its simplicity and because the variation in sound speed with temperature for an ideal gas is well known. The resonator was placed in a Dewar flask and a small quantity of liquid nitrogen was introduced to cool the resonator. Once the temperature stabilized, the computer system was activated and the lowest three plane-wave resonance modes were tracked as the system warmed. This tracking and recording of data proceeded unassisted by the operator for approximately twenty-two hours. At the end of this period, the resonator had reached room temperature and the process was halted. The printout was examined and the data tape was utilized to produce Figures 10 through 14 on the system plotter to demonstrate the utility of the system.

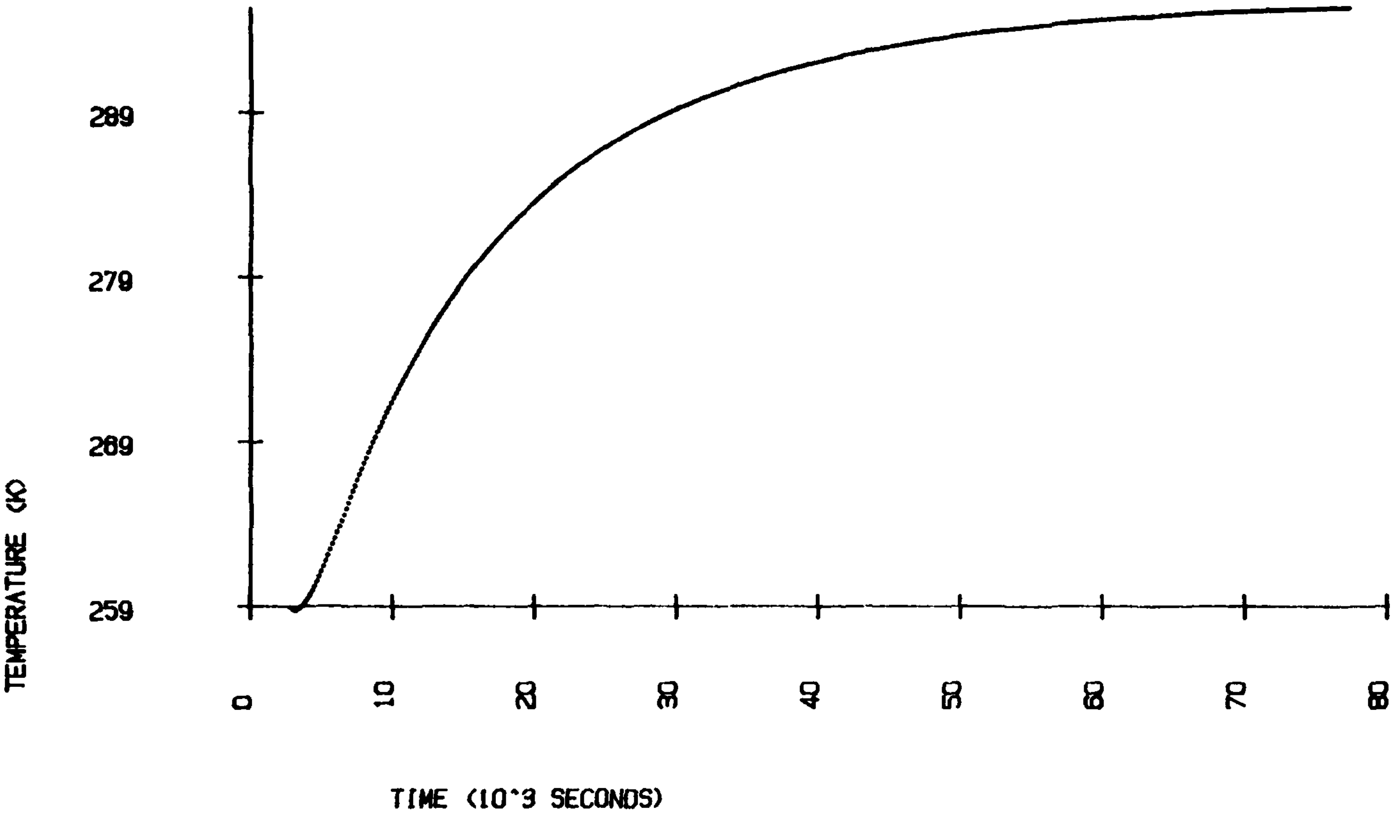
Figure 10 shows a point by point plot of temperature in degrees Kelvin versus time in seconds. After time 10,000, the curve begins to appear as a solid line because the individual points become too closely grouped together to be

visually distinguished in the plot. This likewise occurs at varying places in the other figures. Also, in Figure 10, there is a slight dip at the beginning of the curve because the system was activated as the temperature was still slightly decreasing vice stable as described above.

Figure 11 shows a plot of the log of the difference between a reference temperature (at infinite time) and each individually measured temperature, versus time. This plots as a nearly straight line whose slope is a measure of the exponential thermal equilibrium time.

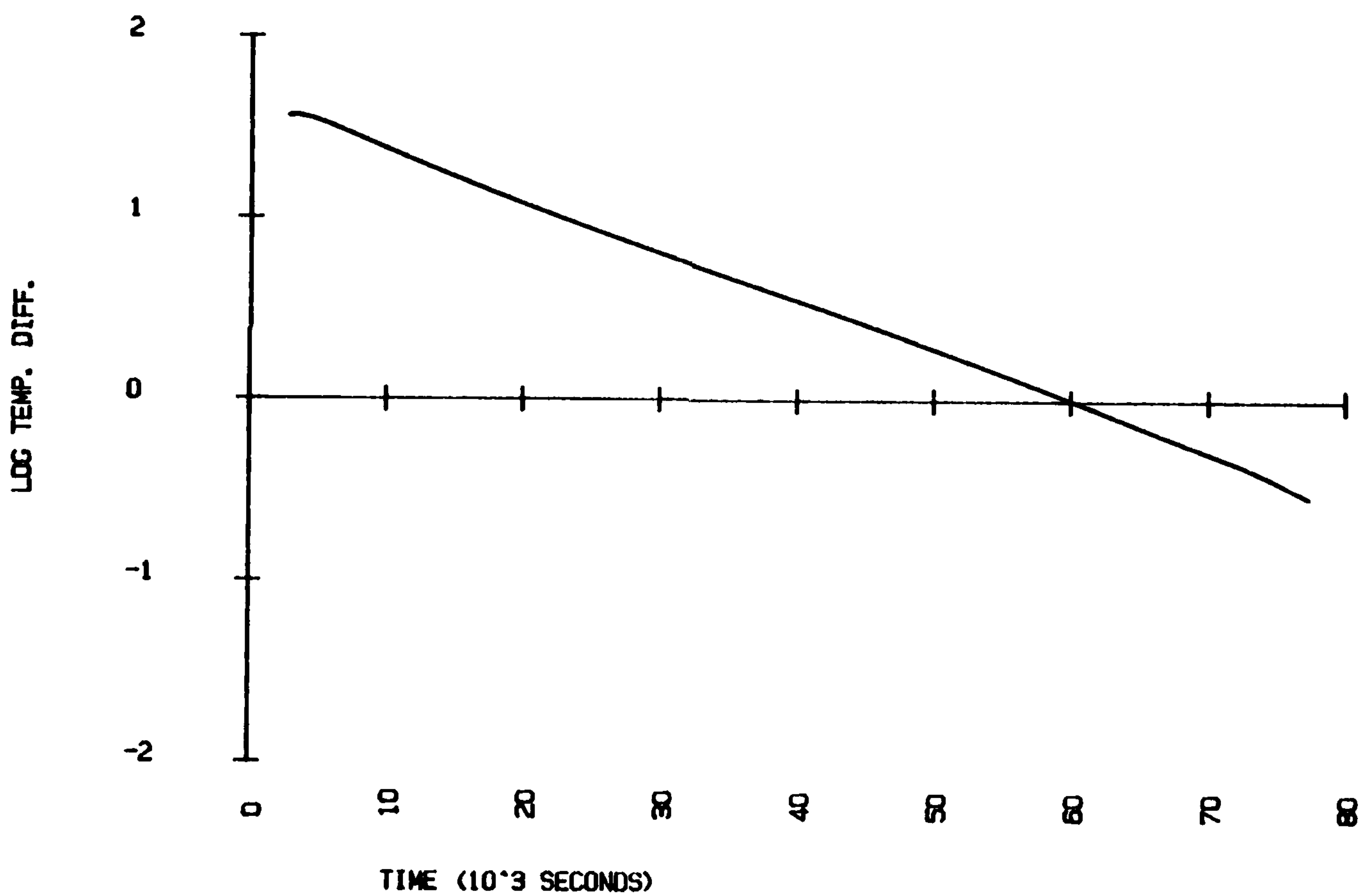
Figures 12, 13, and 14 show plots of the square of the normalized frequencies of each mode $(fo/M\#)^2$ versus the absolute temperature. For an ideal gas these plots should be straight lines. In a perfect resonator, each successive resonant mode would be an exact multiple of the first and the normalized frequencies would lie identically upon one another. In this experiment mode two is parallel to mode one but slightly higher in normalized value while mode three lies diagonally in-between mode one and mode two. Because the exact physical properties of the resonator itself were not being investigated, this was not persued further. The slight curvature of the lines is probably due to the fact

FIGURE 10



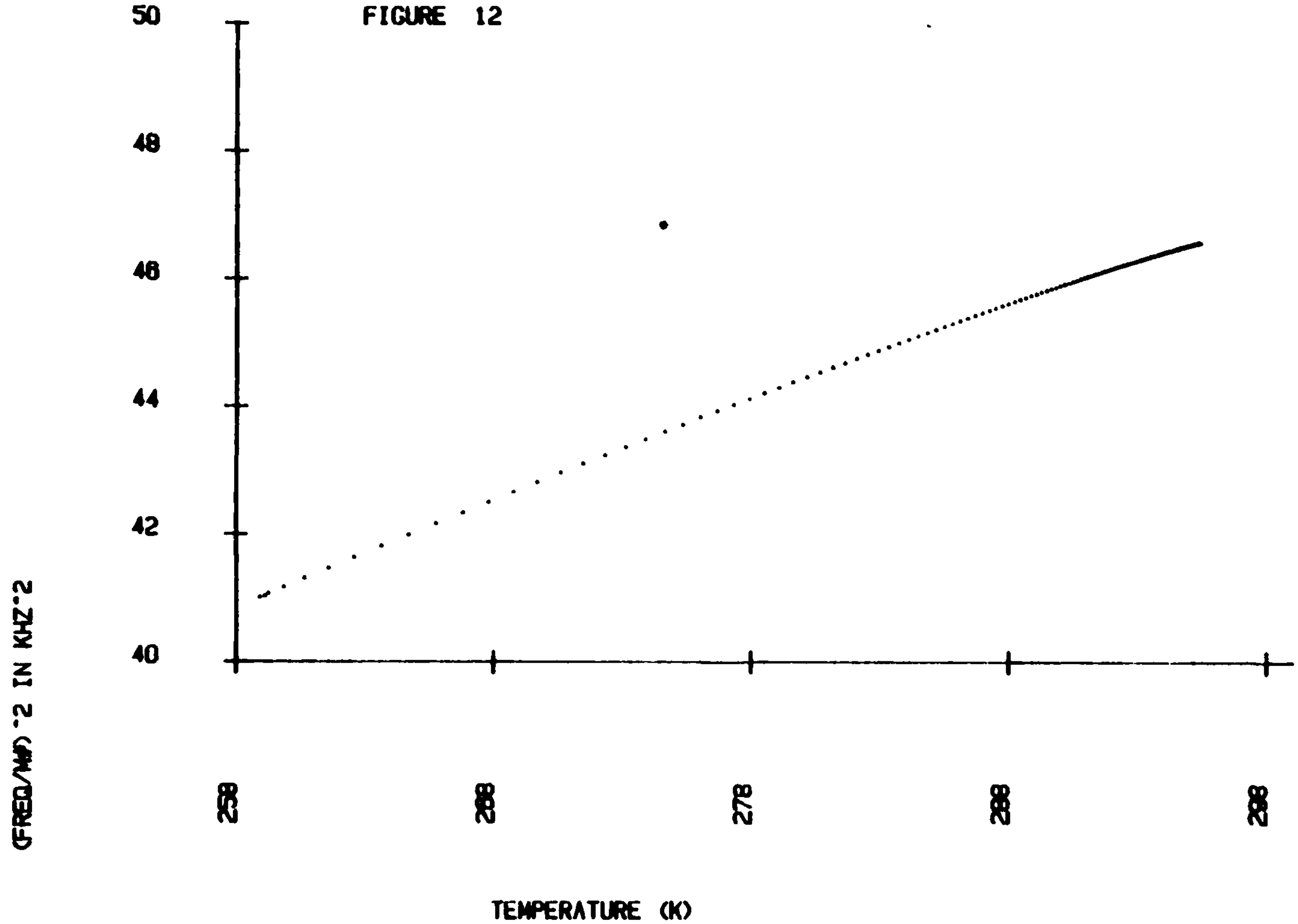
PLOT OF TEMPERATURE VS TIME

FIGURE 11



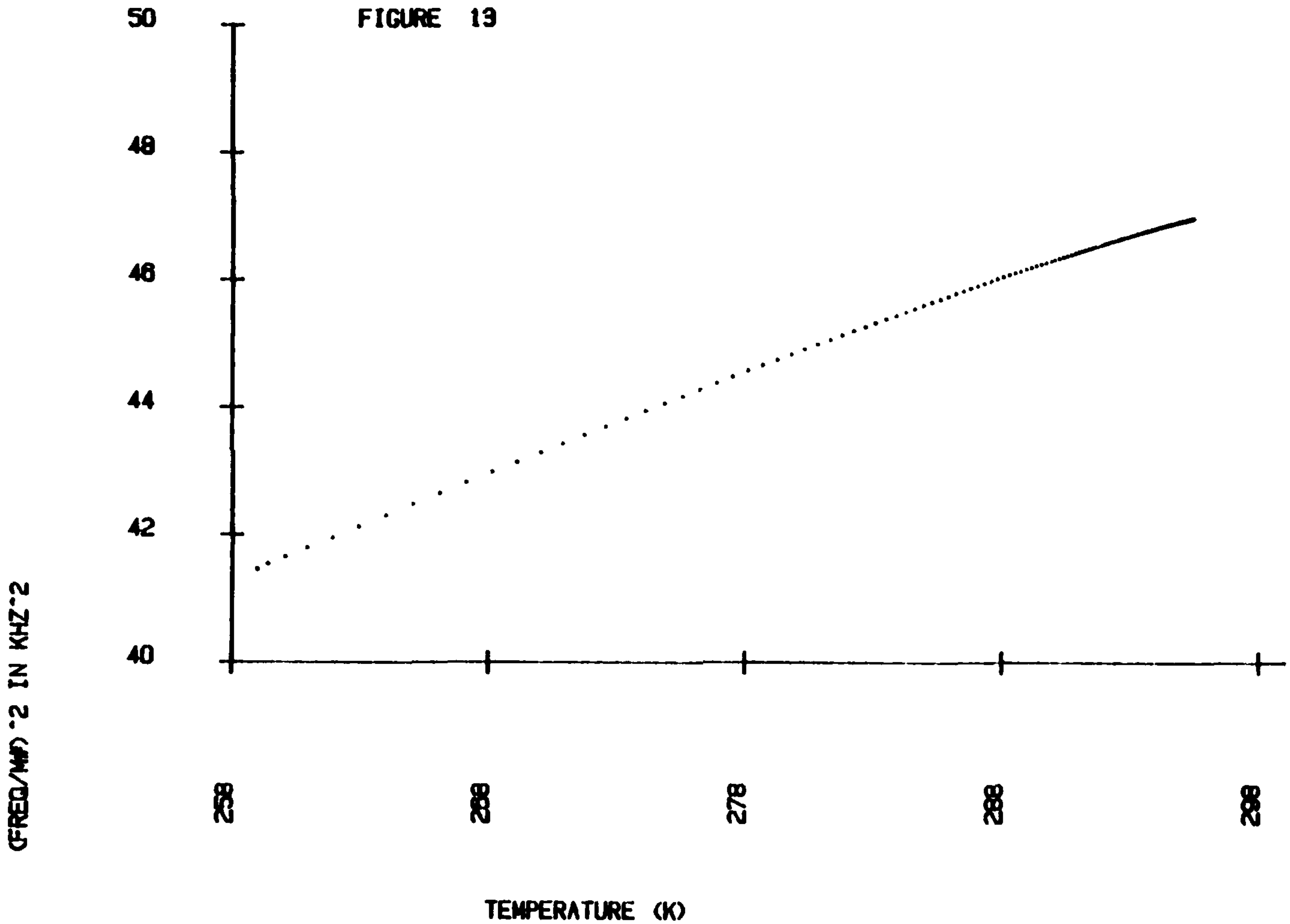
PLOT OF LOG TEMP DIFF VS TIME

FIGURE 12



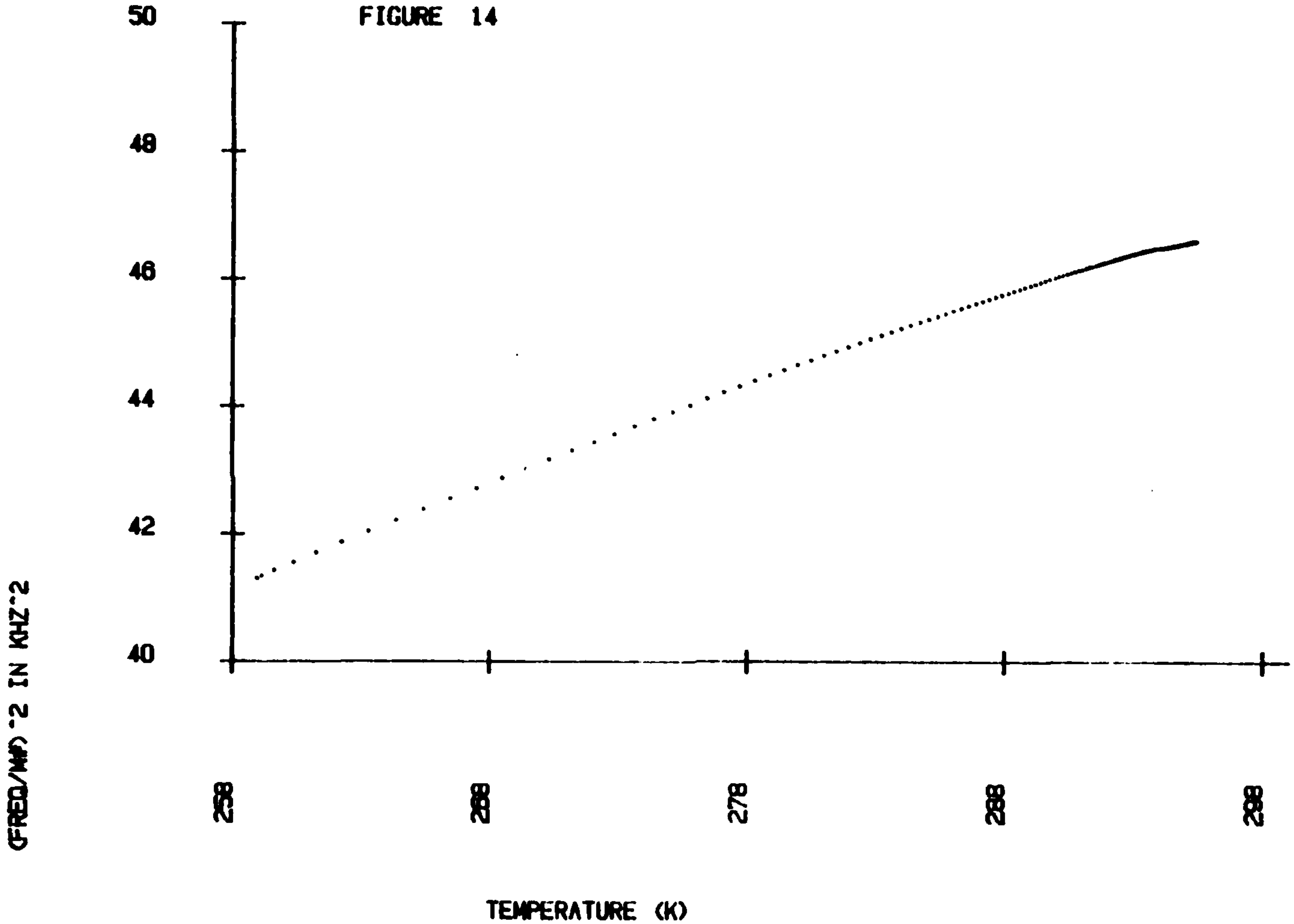
PLOT OF FREQ^2 VS TEMP.MODE 1

FIGURE 13



PLOT OF FREQ^2 VS TEMP.MODE 2

FIGURE 14



PLOT OF FREQ^2 VS TEMP. MODE 3

that the thermistor does not indicate absolute temperature exactly. The slope of the lines and the length of the resonator could be utilized to determine the constants in the ideal gas equation of state.

These figures (10 through 14) demonstrate a few of the possible means of displaying the data stored on the tape. It is intended that future users will determine what plots are needed and generate them accordingly. The program used to produce one of these plots from the data tape is included in Appendix B.

To enumerate what data is available on the tape, a partial reproduction (dot matrix output is not permitted in this thesis) of the system printer output for another experiment is shown in Table 1. The time shown is the average time at which the measurements were taken. The temperature is the average at which time the measurements were taken (in degrees Celsius). The pressure is set to zero because a varying pressure was not to be evaluated, and thus, a means of detecting pressure was not included in the equipment setup. The next entry in the line is the mode number for which the data applies, followed by the final ravined values for fo, A, and Q. The SNR is obtained from

TABLE 1 SAMPLE SYSTEM PRINTER OUTPUT

TIME (SEC)	TEMP (C)	PRES	M#	C FREQ (HZ)	AMP (Vrms)	Q	SNR	C-G RAVINE
608	23.279	0	1	6834.18130	1.3800E-002	165.5321	16598	3.3652E-004
760	23.320	0	2	13736.34416	1.1085E-002	100.5531	13332	4.3282E-004
913	23.356	0	3	20507.15948	1.4333E-002	85.3502	17239	1.4849E-005
1306	23.580	0	1	6837.95165	1.3925E-002	164.5812	16748	3.3880E-004
1459	23.614	0	2	13742.97756	1.1234E-002	100.7451	13511	4.3327E-004
1613	23.626	0	3	20524.59757	1.4332E-002	84.3916	17238	1.3125E-005
5278	23.827	0	1	6840.48173	1.4148E-002	164.4153	17017	3.8203E-004
5432	23.835	0	2	13747.87790	1.1328E-002	100.6442	13624	4.3344E-004
5587	23.842	0	3	20524.59757	1.4381E-002	83.7679	17297	7.3880E-006

the division of A by the value found for the noise (as explained in Chapter III). The next value on a normal printout would be the drive amplitude of the system followed by the sequentially increasing number of the data tape item. These two items were deleted from this figure in order to conform to thesis requirements without requiring photo reduction. The whole line constitutes one data item so far as the tape limit of 350 data items are concerned. However, each item in the line is an actual separate entry within each of the data items. The final entry is the C-G 'Ravine' value.

Table 2 is a reproduction of the output obtained from the HP-85 thermal printer during the course of an experiment. For further amplification of each of the entries, the reader is directed to Chapter III, sections B, C, and D. The system printer was utilized for this figure again because dot matrix outputs are not permitted in this thesis.

TABLE 2 SAMPLE OUTPUT OF HP-85 THERMAL PRINTER

AMPLITUDE IN VOLTS	FREQUENCY
.01082875	6817.00
.00829425	6896.00
.01058175	13769.00
.00820725	13848.00
.00828725	20405.00
.01466500	20484.00
.02054900	20563.00
.01539075	20642.00
.00889400	20721.00

MODE 1 CENTER FREQ IS 6830 AND AMP IS .0181355 Q IS 190.123117729

MODE 2 CENTER FREQ IS 13758 AND AMP IS .0127195 Q IS 135.493980736

MODE 3 CENTER FREQ IS 20540 AND AMP IS .02531475 Q IS 194.224445807

TIME CONST > = 8.86082488511 NEW TIME CONST IS 10

The mean is .000378581 The standard dev is 9.7975285484E-7

NO. OF POINTS FOR MODE 1 IS 212 NO. CHOSEN IS 24

NO. OF POINTS FOR MODE 2 IS 177 NO. CHOSEN IS 24

NO. OF POINTS FOR MODE 3 IS 250 NO. CHOSEN IS 24

V. EVALUATION AND RECOMMENDATIONS

This section describes the method utilized to determine the "goodness of fit" and the resulting precision. The program previously described was utilized in a steady state condition (no variation of external parameters). Also, 'Ravine' was programmed for fifteen iterations per mode, with a printout of the Q, A, and fo values for each iteration. In this manner the change per iteration could be evaluated for each of the variables. As stated previously, 'Ravine' is completed (C-G minimized) when successive iterations produce a negligible variation in the value obtained [Ref. 3]. For a given sample run, the variation between the fourteenth and fifteenth iteration ((15-14)/15) was approximately one in one million (mode 1) to one in ten million (mode 2) for Q, one in two million (mode 1) to one in fifteen million (mode 3) for A, and one in six billion (mode 1) to one in one hundred thiry-seven billion (mode 2). It is evident that the change per iteration is definitely small and thus the fifteenth iteration values were utilized as a base line for the calculation of precision to follow.

TABLE 3 COMPARISON OF PRECISION OF ITERATIONS

	MODE 1	MODE 2	MODE 3
	Q	Q	Q
3rd/15th	1.04E-3	8.94E-5	1.25E-4
5th/15th	3.85E-4	3.31E-5	4.64E-5
	A	A	A
3rd/15th	4.66E-4	2.85E-5	3.99E-5
5th/15th	1.72E-4	1.05E-5	1.47E-5
	f	f	f
3rd/15th	1.20E-7	3.62E-9	1.54E-8
5th/15th	4.45E-8	1.34E-9	5.71E-9

Each C-G ravine value for the third and fifth iteration was compared to the base line to determine the precision of the system. This was accomplished by taking the ratio of the difference of the base line and the iteration to the base line value. Table 3 shows the approximate (rounded) values obtained for each by mode. This represents a best/worst precision of one in ten thousand/one in one thousand for Q, of one in thirty thousand/one in two thousand for A, and one in three hundred million/one in one million for fo for the third iteration. The program, as presented, stops after the third iteration because each full iteration requires 45 seconds on the HP-85 and that was the point chosen in the precision/time trade-off for this particular application. This will be further discussed at the end of this chapter. The results for the fifth iteration (in the same manner) are one in thirty thousand/one in three thousand for Q, one in one hundred thousand/one in five thousand for A, and one in five hundred million/ one in twenty million for fo.

Precision has been discussed since it is independent of the equipment utilized. Accuracy, on the other hand,

involves not only the precision to which any given instrument measures as well as that of the overall system but also the accuracy of each measurement and the accuracy of the overall system. For example, this system will measure the given value of the temperature to within more than five significant figures between -80 degrees and 150 degrees Celsius, yet, it is only accurate to within six degrees Celsius (a function of the thermistor). Thus, there is a dramatic difference between precision and accuracy.

A. CONCLUSIONS AND RECOMMENDATIONS

The ability of this system to obtain Q, A, and fo far surpasses that of any manual method. In addition, it allows the operator to perform additional functions as the experiment progresses, does not make transcription/interpretation errors as is possible/likely with manual recording of data, gives highly reproducible results independent of the skill of the operator, and allows for the resulting data to be to be easily presented in a variety of formats in a very short period of time.

It was originally intended that this complete system be a prototype to then be transferred to a system utilizing the HP9836 rather than the HP-85. However, the equipment

arrived too late to be incorporated. One major advantage of the HP9836 is that it has an eight-to-one speed advantage over the HP-85. Speed is the reason that only three rather than five iterations of 'Ravine' were utilized. Since each mode took approximately 135 seconds, 6.75 minutes elapsed from the start of 'Measure', Mode 1, to the next start of 'Measure', Mode 1. Obviously, the greater the number of modes the greater the time required. This time diffference could be a major problem if the changing external parameter caused the resonance of the modes to shift significantly so that the response no longer fitted within the chosen bandwidth. One method of overcoming this would be to incorporate a prediction of the next location based upon the change of the parameter. This was not incorporated in this program for two reasons. One, it was never necessary in the experiment run; and two, the shift to the HP9836 with its speed advantage would eliminate this lengthy time period (it could perform twenty-four modes in the same period it presently takes for three).

Another future change could be to work in 'Ravine' for the first set of data while taking the measurements for the second set of data. This would be a better utilization of

computer time since there are currently periods when the computer is idle (WAIT periods and time constants).

Another improvement would be to replace the lock-in analyzer with a computer controllable model. This is, of course, a trade-off of price versus convenience/time since there is approximately a two-to-one ratio in equipment cost.

There are also numerous computer programming techniques which could shorten portions of the program and/or associated run times. One obvious change would be to make CRT presentations of graphs optional or, if the system under test was already well known, to make the option available to enter the program at the 'NEW TAU' point thus eliminating the need to establish the desired mode data. This was not done in the presented program since it will be utilized by a variety of users and each will be able/is encouraged to make modifications for specific applications.

APPENDIX A

REFERENCE GUIDE TO PROGRAM LISTING

Line Nos.	Description
1 - 251	INPUT
270 - 640	SEARCH
650 - 1690	SORT
1691 - 1899	NEW TAU
1900 - 2676	MEASURE
2679 - 4997	RAVINE
4998 - 5320	TRACK

```
1 DIM F4(300),A(300),C(100)
2 CLEAR
3 PRINTER IS 2
4 OUTPUT 722 ;"F4M6"
5 DISP "REMOVE PROGRAM TAPE AND INSTALL DATA TAPE" @ BEE
P
6 DISP "WHEN COMPLETED, ENTER 1"
7 INPUT Y
8 IF Y=1 THEN 9 ELSE CLEAR @ BEEP @ GOTO 2
9 ERASETAPE
10 CREATE "DATA",850,66 @ REWIND
11 CLEAR @ BEEP ! intial set up
13 SETTIME 0,0
21 DISP "Enter lower freq"
31 INPUT F1 ! lower freq
41 CLEAR @ BEEP
51 DISP "Enter upper freq"
61 INPUT F2 ! upper freq
71 IF F2<=F1 THEN CLEAR @ BEEP @ GOTO 51
81 T=1/(4*((F2-F1)/256)) ! time constant
91 CLEAR @ BEEP
101 DISP "Set time constant on 5204 at ";T;" or smaller"

111 DISP "When complete, enter value set (in Milli-sec)"

121 INPUT T1
131 IF T1>T*1000 THEN CLEAR @ BEEP @ GOTO 101
141 CLEAR @ BEEP
151 DISP "Enter amp of driving freq in mv (=<3500)RMS"
161 DISP "DECIMAL VALUES ARE NOT PERMITTED"
171 INPUT A ! amp of freq
181 IF A>3500 THEN CLEAR @ BEEP @ GOTO 151
182 FOR N=1 TO 9
183 A8(N)=A
184 NEXT N
191 CLEAR @ BEEP
201 DISP "Enter largest value of amp ever desired (=<350
0mv RMS)"
211 INPUT A1 ! max future amp
221 IF A1>3500 THEN CLEAR @ BEEP @ GOTO 201
230 ! these are the values to set up the 3325A
231 A$=VAL$(A)
232 A2$="AM"
233 A3$="MR"
240 OUTPUT 717 ;A2$,A$,A3$
241 WAIT 200
251 F3=CEIL((F2-F1)/256) ! smallest int >= bandwidth
252 ! SEARCH
253 ! SEARCH
254 ! SEARCH
```

```
261 ! next group sends freq to 3325A, and gets amp from
3497A
269 CLEAR
270 DISP "I am working in SEARCH"
271 FOR N=0 TO 256
281 F4(N)=F1+N*F3
282 ! F4(N) is freq sent
290 F4$=VAL$(F4(N))
291 H1$="HZ"
292 H2$="FR"
300 OUTPUT 717 ;H2$,F4$,H1$
310 WAIT 4*T1+100
320 OUTPUT 709 ;"VT3"
330 ENTER 709 ; A(N)
350 NEXT N
351 ! F5 AND F6 ARE SCALE FACTORS
352 BEEP
360 F5=F1-.1*(F2-F1)
370 F6=F2+.1*(F2-F1)
380 GCLEAR @ CLEAR
390 SCALE F5,F6,-.1,1.2
400 XAXIS 0,1000,F1,F2
410 YAXIS F1,.1,-.1,1.2
411 FOR N=0 TO 256
412 PENUP
413 PLOT F4(N),A(N)
414 NEXT N
415 DISP "IF YOU DESIRE A COPY ENTER 1, ELSE ENTER 2",@
BEEP
416 INPUT Y
417 IF Y=2 THEN 477
418 GCLEAR @ CLEAR @ BEEP
419 DISP "ENTER FIGURE # TO BE PRINTED"
420 INPUT L$
421 PLOTTER IS 705
422 PEN 1
423 SCALE F1-.1*(F2-F1),F2+500,-.3,1.3
424 XAXIS 0,1000,F1,F2
425 YAXIS F1,.1,0,1.2
426 PEN 2
427 FOR N=0 TO 256
428 PENUP
429 PLOT F4(N),A(N)
430 NEXT N
431 PENUP @ PEN 1
432 LDIR 0,SIN(90) @ PENUP
433 FOR X=F1 TO F2 STEP 2000 @ PENUP
434 MOVE X,-.13
435 LABEL VAL$(X)
436 NEXT X @ PENUP
```

```
440 LDIR 0
441 FOR Y=0 TO 1.2 STEP .1 & PENUP
442 MOVE F1-.05*(F2-F1),Y
443 LABEL VAL$(Y)
444 NEXT Y @ PENUP
450 LDIR 0 @ PENUP
451 MOVE F1+3000,-.21
452 LABEL "FREQUENCY IN HZ"
453 LDIR 0 @ PENUP
454 MOVE F1,-.3
455 LABEL "PLOT OF RELATIVE AMPLITUDE VS FREQUENCY (FULL
 SPECTRUM)"
456 LDIR 0,SIN(90) & PENUP
457 MOVE F1-.08*(F2-F1),.3
458 LABEL "RELATIVE AMPLITUDE"
459 LDIR 0 @ PENUP
460 MOVE F1+2000,1.2
461 LABEL "FIGURE ";L$
462 PENUP
476 PLOTTER IS 1
477 CLEAR @ BEEP
478 DISP "Do you desire to rerun exp with different para
meters"
479 DISP "If so enter 1, otherwise enter 2"
480 INPUT Y
490 GCLEAR @ CLEAR @ BEEP
500 IF Y=1 THEN 11
510 DISP "Enter decision point for amplitude (0 TO 1.2)"

520 INPUT A4 ! DECISION POINT
530 CLEAR @ BEEP
540 DISP "Enter full-scale sensitivity setting from the
5204 in volts"
550 INPUT A5 ! SENSITIVITY SETTING
560 PRINT "Amplitude in volts";"   Frequency"
570 PRINT
580 FOR N=0 TO 256
590 IF A(N)<A4 THEN 630
600 A(N)=A5*A(N)
610 PRINT USING 620 ; A(N),F4(N)
620 IMAGE 1X,D.DDDDDDDD,10X,DDDDDD.DD
630 NEXT N
631 PRINT USING 632
632 IMAGE 3/
640 CLEAR @ BEEP
641 ! SORT
642 ! SORT
643 ! SORT
650 DISP "How many modes do you desire to track (MAX OF
9)"
```

```
660 INPUT M ! NUMBER OF MODES
670 FOR N=1 TO M
680 CLEAR @ BEEP
690 DISP "what is center freq for mode ";N
700 INPUT M(N) ! CENTER FREQ
710 CLEAR @ BEEP
720 DISP "what is freqwidth for mode ";N
730 DISP "MUST BE GREATER THAN ";2*F3 ! F3 IS BW
740 INPUT O(N) ! FREQ-WIDTH
750 NEXT N
760 CLEAR
761 ! From 770 to 960 is the first rough try for measuri
ng (SCFT)
770 FOR L=1 TO M
771 DISP "I am working in SCFT for mode ";L
780 FOR N=0 TO 100
790 F4(N)=M(L)-O(L)/2+N*O(L)/100
800 F4$=VAL$(F4(N))
810 OUTPUT 717 ;H2$,F4$,H1$
820 WAIT 12*T1+100
830 OUTPUT 709 ;"VT3"
831 WAIT 50
840 ENTER 709 ; A(N)
850 NEXT N
851 BEEP
860 GCLEAR @ CLEAR
870 SCALE F4(0)-.1*O(L),F4(100)+.1*O(L),-.1,1.2
880 XAXIS 0,O(L)/10,F4(0),F4(100)
890 YAXIS F4(0),.1,0,1.2
900 FOR N=0 TO 100
910 PENUP
920 PLOT F4(N),A(N)
930 NEXT N
940 MOVE F4(0),-.1
941 LABEL "MODE ";L;" ";F4(0);" TO ";F4(100)
942 DISP "IF YOU WANT A COPY ENTER 1, ELSE ENTER 2",@ BE
EP
943 INPUT Y
944 IF Y=2 THEN 967
945 GCLEAR @ CLEAR @ BEEP
946 DISP "ENTER FIGURE # TO BE PRINTED"
947 INPUT L$
954 PLOTTER IS 705
955 PEN 1
956 SCALE F4(0)-.2*O(L),F4(100)+.1*O(L),-.3,1.3
957 XAXIS 0,O(L)/10,F4(0),F4(100)
958 YAXIS F4(0),.1,0,1.2
959 PEN 2
960 FOR N=0 TO 100
961 PENUP
```

```
962 PLOT F4(N),A(N)
963 NEXT N
964 PENUP @ PEN 1
965 LDIR 0,SIN(90)
966 FOR X=F4(0) TO F4(100) STEP C(L)/10 @ PENUP
967 MOVE X,-.13
968 LABEL VAL$(X)
969 NEXT X
970 LDIR 0 @ PENUP
971 FOR Y=0 TO 1.2 STEP .1 @ PENUP
972 MOVE F4(0)-.08*C(L),Y
973 LABEL VAL$(Y)
974 NEXT Y
975 LDIR 0 @ PENUP
976 MOVE F4(0)+.1*C(L),-.21
977 LABEL "FREQUENCY IN HZ"
978 LDIR 0 @ PENUP
979 MOVE F4(0)-.1*C(L),-.3
980 LABEL "PLOT OF RELATIVE AMPLITUDE VS FREQUENCY, MODE
 ";L
981 LDIR 0,SIN(90) @ PENUP
982 MOVE F4(0)-.17*C(L),.3
983 LABEL "RELATIVE AMPLITUDE "
984 LDIR 0 @ PENUP
985 MOVE F4(0)+.1*C(L),1.2
986 LABEL "FIGURE ";L$ @ PENUP @ PLOTTER IS 1
987 CLEAR @ BEEP
988 DISP "Do you want to change anything. If so enter 1,
 else 2"
989 INPUT Y@ CLEAR @ BEEP
990 IF Y=2 THEN 1200
1000 DISP "Change sensitivity? Enter 1 for yes, 2 for no
"
1010 INPUT Y@ CLEAR @ BEEP
1020 IF Y=2 THEN 1060
1030 CLEAR @ BEEP
1040 DISP "Enter new sensitivity setting"
1050 INPUT A5
1060 CLEAR @ BEEP
1070 DISP "Change freqwidth? Enter 1 for yes, 2 for no"
1080 INPUT Y@ CLEAR @ BEEP
1090 IF Y=2 THEN 1120
1100 DISP "Enter new freqwidth"
1110 INPUT C(L)
1120 CLEAR @ BEEP
1130 DISP "Change center freq? Enter 1 for yes, 2 for no
"
1140 INPUT Y@ CLEAR @ BEEP
1150 IF Y=2 THEN 1180
1160 DISP "Enter new center freq"
```

```
1170 INPUT F(L)
1180 GCLEAR @ CLEAR
1190 GOTO 771
1191 ! From 1200 to 1660 is the first try at getting cen
ter freq and the Q
1200 CLEAR @ GCLEAR
1201 DISP "I am working on freq and Q for SORT mode ";L
1210 H,B1,B4,H1,H2,H3,H4=0
1220 B2,B3=50
1230 FOR N=1 TO 100
1240 IF A(N)<A(H) THEN 1280
1241 IF A(N)=A(H) THEN 1242 ELSE 1250
1242 PRINT A(N)
1250 A6(L)=A(N)
1260 F6(L)=F4(N)
1270 H=N
1280 NEXT N
1290 A7(L)=A6(L)/SQR(2)
1300 FOR N=0 TO H
1310 IF A7(L)=A(N) THEN 1410
1320 IF A7(L)<A(N) THEN 1370
1330 IF A(N)<B1 THEN 1450
1340 B1=A(N)
1350 H1=N
1360 GOTO 1450
1370 IF A(N)>B2 THEN 1400
1380 B2=A(N)
1390 H2=N
1400 GOTO 1450
1410 B1,B2=A(N)
1420 H1,H2=N
1430 F7=F4(H2)
1440 GOTO 1470
1450 NEXT N
1451 X=(A7(L)-B1)/(B2-B1)
1460 F7=X*(F4(H2)-F4(H1))+F4(H1)
1470 FOR N=H TO 100
1480 IF A7(L)=A(N) THEN 1580
1490 IF A7(L)>A(N) THEN 1540
1500 IF A(N)>B3 THEN 1530
1510 B3=A(N)
1520 H3=N
1530 GOTO 1620
1540 IF A(N)<=B4 THEN 1570
1550 B4=A(N)
1560 H4=N
1570 GOTO 1620
1580 B3,B4=A(N)
1590 H3,H4=N
1600 F8=F4(H3)
```

```
1610 GOTO 1640
1620 NEXT N
1621 X=(A7(L)-B4)/(B3-B4)
1630 F8=-(X*(F4(H4)-F4(H3)))+F4(H4)
1640 Q(L)=F6(L)/(F8-F7)
1650 PRINT "MODE ";L;
1660 PRINT "CENTER FREQ IS ";F6(L);" AND AMP IS ";A6(L)*
A5
1670 PRINT "Q IS ";Q(L)
1671 CLEAR
1672 PRINT USING 1673
1673 IMAGE 5/
1680 NEXT L
1690 CLEAR & GCLEAR
1691 DISP "I am working on time constant"
1699 ! From 1700 to 1740 the largest Time Constant is fo
und
1700 FOR L=1 TO M
1701 T(L)=Q(L)/(PI*F6(L))
1702 NEXT L
1705 T=T(1)
1710 FOR L=2 TO M
1711 IF T>T(L) THEN 1720
1712 T=T(L)
1720 NEXT L
1750 BEEP & CLEAR
1755 PRINT "TIME CONST >= ";T*1000
1760 DISP "Set and enter new time constant (in milli-sec
)"
1770 DISP "MUST BE GREATER THAN ";T;" sec"
1780 INPUT Y
1790 T1=Y
1791 CLEAR
1792 PRINT "NEW TIME CONST IS ";T1
1793 PRINT USING 1794
1794 IMAGE 4/
1795 ! MEASURE
1796 ! MEASURE
1797 ! MEASURE
1798 ! MEASURE
1799 DISP "I am working on standard dev, # of pts, & var
iance "
1800 ! From 1800 to 1924 is the calc of the noise, st. d
ev., and the number of pts. used.
1801 G,W=0
1802 F=(F6(2)-F6(1))/4+F6(1)
1803 F4$=VAL$(F)
1804 OUTPUT 717 ;H2$,F4$,H1$
1805 WAIT T1*12+100
1806 OUTPUT 709 ;"V11"
```

```
1807 WAIT 1000
1808 FOR N=1 TO 100
1809 ENTER 709 ; A(N)
1810 W=W+A(N)
1811 NEXT N
1812 W=W/100
1813 FOR N=1 TO 100
1814 S=(A(N)-W)^2
1815 G=G+S
1816 NEXT N
1817 G=A5*SQR(G/99)
1818 W=W*A5
1819 PRINT "The mean is ";W
1820 PRINT "The standard dev is ";G
1821 PRINT USING 1822
1822 IMAGE 4/
1825 FOR L=1 TO M
1830 I(L)=1.82*SQR(A6(L)*A5/G)
1835 PRINT "NO. OF POINTS FOR MODE ";L;" IS ";I(L)
1840 IF I(L)<100 THEN 1850
1845 I(L)=100
1850 IF I(L)>50 THEN 1860
1855 I(L)=50
1860 I(L)=IP(I(L))
1861 I(L)=24
1864 PRINT "NO. CHOSEN IS ";I(L)
1865 PRINT
1866 NEXT L
1867 CLEAR @ BEEP
1880 PRINT USING 1881
1881 IMAGE 4/
1885 PRINTER IS 701,132
1887 DIM F$[20]
1888 F$="C-G FAVINE"
1890 PRINT USING 1891 ; "TIME","TEMP","PRES","M #","C. F
REQ","AMP.","Q","SNR","D-AMP","# PT",F$
1891 IMAGE 4A,5X,4A,6X,5A,4X,3A,6X,7A,9X,4A,14X,1A,9X,3A
,5X,5A,4X,4A,6X,10A
1892 PRINT USING 1893 ; "(SEC)","( C )","(HZ)","(Vrms)",
"(mV)"
1893 IMAGE 5A,4X,5A,25X,4A,10X,6A,30X,4A,/
1898 PRINTER IS 2
1899 CLEAR
1900 ! From 1900 to 4960 is the calculation for the meas
ure including center freq and Q
1901 I5=1
1902 FOR L=1 TO M
1903 DISP "I AM IN MEASURE FOR MODE ";L
1906 F1=F6(L)-F6(L)/Q(L)
1907 F2=F6(L)+F6(L)/Q(L)
```

```
1908 U=(F2-F1)/I(L)
1909 V=(F2-F1)/2
1910 H=0
1911 IF A6(L)>.3 THEN 1917
1912 A8(L)=2*A8(L)
1913 A6(L)=2*A6(L)
1914 IF A8(L)<A1 THEN 1911
1915 A8(L)=A1
1916 GOTO 1925
1917 IF A6(L)<.95 THEN 1925
1918 A8(L)=A8(L)/2
1919 A6(L)=A6(L)/2
1920 GOTO 1917
1925 A$=VALS(A8(L))
1926 OUTPUT 717 ;A2$,A$,A3$
1927 WAIT 200
1928 ENTER 722 ; T6
1929 FOR N=0 TO I(L)
1930 F4(N)=F6(L)+U*N-V
1931 F4$=VALS(F4(N))
1932 H1$="HZ"
1933 H2$="FR"
1934 OUTPUT 717 ;H2$,F4$,H1$
1935 WAIT 12*T1+100
1936 OUTPUT 709 ;"VT3"
1937 ENTER 709 ; A(N)
1938 NEXT N
1939 ENTER 722 ; T2
1940 FOR N=1 TO I(L)
1941 IF A(N)<A(H) THEN 1960
1942 IF A(N)=A(H) THEN 1943 ELSE 1950
1943 PRINT A(N)
1950 H=N
1960 NEXT N
1970 X=A(H)
1980 Y=(A(H+1)-A(H-1))/2
1990 Z=(A(H+1)+A(H-1)-2*X)/2
2000 F6(L)=-(Y/(2*Z))
2010 A6(L)=X+Y*F6(L)+Z*F6(L)^2
2020 F6(L)=F4(H)+F6(L)*(F4(H)-F4(H-1))
2030 B1,B4,H1,H2,H3,H4=0
2040 B2,B3=50
2290 A7(L)=A6(L)/SQR(2)
2300 FOR N=0 TO H
2310 IF A7(L)=A(N) THEN 2410
2320 IF A7(L)<A(N) THEN 2370
2330 IF A(N)<B1 THEN 2450
2340 B1=A(N)
2350 H1=N
2360 GOTO 2450
```

```
2370 IF A(N)>B2 THEN 2400
2380 B2=A(N)
2390 H2=N
2400 GOTO 2450
2410 B1,B2=A(N)
2420 H1,H2=N
2430 F7=F4(H2)
2440 GOTO 2470
2450 NEXT N
2451 X=(A7(L)-B1)/(B2-B1)
2460 F7=X*(F4(H2)-F4(H1))+F4(H1)
2470 FOR N=H TO I(L)
2480 IF A7(L)=A(N) THEN 2580
2490 IF A7(L)>A(N) THEN 2540
2500 IF A(N)>B3 THEN 2530
2510 B3=A(N)
2520 H3=N
2530 GOTO 2620
2540 IF A(N)<=B4 THEN 2570
2550 B4=A(N)
2560 H4=N
2570 GOTO 2620
2580 B3,B4=A(N)
2590 H3,H4=N
2600 F8=F4(H3)
2610 GOTO 2640
2620 NEXT N
2621 X=(A7(L)-B4)/(B3-B4)
2630 F8=-(X*(F4(H4)-F4(H3)))+F4(H4)
2640 Q(L)=F6(L)/(F8-F7)
2673 PRINTER IS 701,132
2676 CLEAR
2677 !
2678 !
2679 ! VARY Q
2680 FOR B=1 TO 3
2685 FOR K=1 TO 3
2689 DISP "I AM IN RAVINE FOR Q OF MODE ";L
2690 J(1)=Q(L)
2700 J(2)=1.005*Q(L)
2710 J(3)=.995*Q(L)
2711 R=A6(L)
2712 U=(1/J(K))^2
2720 E(K)=0
2730 FOR N=1 TO I(L)
2740 C(N)=R/(J(K)*SQR((F4(N)/F6(L)-F6(L)/F4(N))^2+U))
2750 D=(A(N)-C(N))^2
2760 E(K)=E(K)+D
2770 NEXT N
2775 CLEAR
```

```
2780 NEXT K
2813 V=-((E(2)-E(3))/(2*(E(2)+E(3)-2*E(1))))
2814 Q(L)=J(1)+V*.005*J(1)
2876 !
2877 !
2878 !
2879 ! VARY AMP
2880 CLEAR
2881 FOR K=1 TO 3
2889 DISP "I AM IN RAVINE FOR AMPLITUDE OF MODE ";L
2890 J(1)=A6(L)
2900 J(2)=1.002*A6(L)
2910 J(3)=.998*A6(L)
2911 U=(1/Q(L))^2
2920 E(K)=0
2930 FOR N=1 TO I(L)
2940 C(N)=J(K)/(Q(L)*SQR((F4(N)/F6(L)-F6(L)/F4(N))^2+U))

2950 D=(A(N)-C(N))^2
2960 E(K)=E(K)+D
2970 NEXT N
2975 CLEAR
2980 NEXT K
3020 V=-((E(2).-E(3))/(2*(E(2)+E(3)-2*E(1))))
3030 A6(L)=J(1)+V*.002*J(1)
3176 !
3177 !
3178 !
3179 ! VARY FREQ
3180 CLEAR
3181 FOR K=1 TO 3
3189 DISP "I AM IN RAVINE FOR FREQUENCY OF MODE ";L
3190 J(1)=F6(L)
3200 J(2)=.005*F6(L)/Q(L)+F6(L)
3210 J(3)=-(.005*F6(L)/Q(L))+F6(L)
3211 R=A6(L)
3212 U=(1/Q(L))^2
3220 E(K)=0
3230 FOR N=1 TO I(L)
3240 C(N)=R/(Q(L)*SQR((F4(N)/J(K).-J(K)/F4(N))^2+U))
3250 D=(A(N)-C(N))^2
3260 E(K)=E(K)+D
3270 NEXT N
3275 CLEAR
3280 NEXT K
3305 V=-((E(2).-E(3))/(2*(E(2)+E(3)-2*E(1))))
3306 F6(L)=J(1)+V*.005*J(1)/Q(L)
3307 NEXT E
3308 !
3309 !
```

```
3310 !
3311 ! LAST SHOT RAVINE #
3312 CLEAR
3314 DISP "I AM IN LAST SHOT R"
3316 U=A6(L)
3317 G=(1/Q(L))^2
3318 E=0
3319 FOR N=1 TO I(L)
3320 C(N)=U/(Q(L)*SQR((F4(N)/F6(L)-F6(L)/F4(N))^2+G))
3321 D=(A(N)-C(N))^2
3322 E=E+D
3323 NEXT N
3326 U=U*A5
3327 Y=U/G
3328 DIM G$[132]
3350 ASSIGN# 1 TO "DATA"
3360 T4=TIME
3371 T7=(T5+T6)/2
3380 P5=0
3390 PRINT# 1,I5 ; T4,T7,P5,L,F6(L),U,Q(L),Y,A6(L),I5,E
3400 ASSIGN# 1 TO *
3401 G$="5D,2X,3D.3D,2X,D.3DE,2X,2D,4X,3DC3D.3D,4X,D.4DE
,6X,3D.4D,3X,3DC3D,3X,4D,5X,3D,6X,D.4DE"
3402 PRINT USING G$ ; T4,T7,P5,L,F6(L),U,Q(L),Y,A6(L),I5
,E
3410 I5=I5+1
3420 F4$=VAL$(F6(L))
3430 A$=VAL$(A6(L))
3440 OUTPUT 717 ;A2$,A$,A3$
3450 WAIT 200
3460 OUTPUT 717 ;B2$,F4$,H1$
3470 WAIT T1*16+100
3480 OUTPUT 709 ;"VT3"
3490 ENTER 709 ; C8(L)
4979 PRINTER IS 2
4980 CLEAR
4981 NEXT L
4982 PRINTER IS 701
4983 PRINT USING 4984
4984 IMAGE /
4985 PRINTER IS 2
4995 !
4996 !
4997 !
4998 ! TRACK
5000 T9=0
5010 FOR L=1 TO N
5011 DISP "I AM TRACKING MODE ";L
5020 F4$=VAL$(F6(L))
5030 A$=VAL$(A6(L))
```

```
5040 OUTPUT 717 ;A2$,A$,A3$
5041 WAIT 200
5050 OUTPUT 717 ;B2$,B4$,B1$
5060 WAIT T1*16+100
5061 OUTPUT 709 ;"VT3"
5070 ENTER 709 ; A9
5080 IF A9<=.9*C8(L) THEN 5110
5090 IF A9>=1.1*C8(L) THEN 5110
5100 GOTO 5245
5110 T9=1
5120 IF A9>.3 THEN 5210
5130 A8(L)=2*A8(L)
5140 A9=2*A9
5150 IF A8(L)<A1 THEN 5120
5160 A8(L)=A1
5170 GOTO 5250
5210 IF A9<.95 THEN 5245
5220 A8(L)=A8(L)/2
5230 A9=A9/2
5240 GOTO 5210
5245 CLEAR
5250 NEXT L
5260 ENTER 722 ; T6
5270 IF ABS(T6-T7)>=.2 THEN 1902
5290 IF T9<1 THEN 5010
5300 PRINTER IS 2
5301 T4=TIME
5310 PRINT "GONE TO MEASURE DUE TO AMPLITUDE AT TIME ";T
4
5320 GOTO 1902
6990 CLEAR ; GCLEAR
6999 DISP "THE END"
9000 END
```

APPENDIX B

A sample program is listed for obtaining information from the data tape and utilizing it in a figure or plot. The key spot in this program is at line 31, the reading of data from the tape. There are a maximum of 850 records on the tape. In this case, I5 is indicating which record is to be accessed. Each of these records can be accessed in a random manner. Only the actual value is stored, not the specific variable that represents it. Thus for example, if in the original storage program the values F = 1, T = 3, G = 4, and B = 7 were stored, only the actual values would be stored in the order given (1,3,4,7). When reading these values from the tape, the 1st value might be called A, the second Z, etc. The important point is that if the 4th entry in the record is desired, four values must be read into memory (read n values to get nth value) and whatever the reading program calls the entry, is what it now must be referred to within the program.

```
1 CLEAR @ BEEP @ GCLEAR
2 DISP "HOW MANY POINTS ARE BEING EVALUATED? ENTER NUMBE
R"
3 INPUT B
4 CLEAR
5 DISP "ENTER THE LOWEST TEMP DESIRED ON PLOT"
6 INPUT B1
7 CLEAR @ BEEP
8 DISP "ENTER THE HIGHEST TEMP DESIRED ON PLOT"
9 INPUT B2
10 CLEAR @ BEEP
17 DISP "ENTER THE MODE # DESIRED"
18 INPUT G
19 CLEAR
21 DISP "ENTER THE FIGURE # DESIRED TO BE PRINTED"
22 INPUT B9
23 CLEAR
27 DIM T1(851),T2(851)
28 GCLEAR @ CLEAR
29 ASSIGN# 1 TO "DATA"
30 FOR I5=1 TO B
31 READ# 1,I5 ; T4,T7,P5,L,F6
32 IF L=G THEN 40 ELSE 50
40 T1(I5)=(F6/G)^2/10^6
41 T2(I5)=T7+273.16
50 NEXT I5
51 PLOTTER IS 705
52 PEN 1
60 GCLEAR @ CLEAR
61 B7=FLOOR(B1+273.16)
62 B8=CEIL(B2+273.16)
70 SCALE B7-10,B8+5,35,51
80 XAXIS 40,10,B7,B8
90 YAXIS B7,2,40,50
91 LDIR 0,SIN(90) @ PENUP
92 FOR X=B7 TO B8 STEP 10 @ PENUP
93 MOVE X,37.5
94 LABEL VAL$(X)
95 NEXT X
96 LDIR 0
97 FOR Y=40 TO 50 STEP 2 @ PENUP
98 MOVE B7-4,Y
99 LABEL VAL$(Y)
100 NEXT Y
101 LDIR 0 @ PENUP
102 MOVE B7+10,36
103 LABEL "TEMPERATURE (K)"
104 LDIR 0,SIN(90) @ PENUP
105 MOVE B7-8,37
106 LABEL "(FREQ/M#)^2 IN KHZ^2"
```

```
107 LDIR 0 @ PENUP
108 MOVE B7-8,35
109 LABEL "PLOT OF FREQ^2 VS TEMP,MODE ";G
110 LDIR 0 @ PENUP
111 MOVE B7+5,50
112 LABEL "FIGURE ";B9
149 PEN 2
150 FOR N=0 TO B/3-1
151 P=G+3*N
152 PENUP
153 PLOT T2(P),T1(P)
154 NEXT N
155 PENUP
160 CLEAR @ GCLEAR
161 REWIND
162 DISP "ALL DONE, TIME TO GO ON"
170 END
```

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8